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HIGH VELOCITY IMPLANTING OF ANCHORS

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RESEARCH AND TECHNOLOGY DEPARTMENT

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This report is a summary of a theoretical investigation of three ways to avoid the severe problems caused by recoil in the implanting of Propellant Emplaced Anchors (PEA's). It was specifically requested that a launching system modeled after a recoilless rifle be evaluated. While doing this, the conclusion was reached that the recoilless rifle approach was more complicated than necessary, and that the desired performance could be achieved more easily by a direct rocket. The sponsors had suggested a water jet approach using cold high pressure gas to supply the energy, instead of propellant gas. This turned

out to be impractical using the compressed air, but it became very practical using propellant gases.

All of the systems were analyzed and simulated by computer models. All three systems appear reasonable and they all solve the recoil problem. However, the recoilless and the direct rocket have a common problem. Their requirement of a rocket motor with very high thrust (1.6 million pounds) and a very short burning time (40 milliseconds) has no parallel in current rocket technology. Apparent solutions to this problem would require very large structures. In any case, their development promises to be expensive and lengthy. Fortunately, the water jet does not share this problem. Its development should be timely, and costs should be reasonable.

FOREWORD

The work on propellant emplaced anchors (PEA) reported here was funded by the Naval Civil Engineering Laboratory (NCEL) under Amphibious and Advanced Base Technology, PE 62760N, Subproject YF 60.536. The purpose of the work covered by this report is to analyze and evaluate three candidate propulsion systems for PEA's to replace the high pressure gun propulsor now used. These alternate propulsion systems all have the capability to propel the PEA's and to eliminate the recoil problems that trouble existing PEA's. All of the propulsion systems are recoilless. All three propulsion systems were analyzed in depth, and the analyses were implemented into computer programs that can simulate their performance. The results from these computer programs, in turn, were used to make estimates of the size and weights of the competing systems. The final selection of the water jet propulsion system was based on size, weight, and anticipated short development time.

Approved by:

J. F. PROCTOR, Head
Energetic Materials Division

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A-1

CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (Cont'd)

A. INTRODUCTION

I. THE PROBLEM: Newton's Third Law has been formulated in many ways, but they all have the same meaning--all forces are produced in equal and opposite pairs. The action and reaction are exactly equal in magnitude and exactly opposite in direction. Anyone who has fired a gun or rifle much larger than .22 caliber understands Newton's Third Law. The high pressure gases from the burning propellant act both on the base of the bullet and the base of the gun breech, producing equal forces on both. Since the bullet is free to move, the force drives it down the barrel and out the muzzle. The person firing the gun is not usually free to move very far because he is coupled to the earth (Figure 1). The recoil force is transmitted through the shooter's body to the earth. If the bullet is a .30 caliber with a weight of 150 grains and a muzzle velocity of 3,000 ft/s, the recoil force will change the earth's velocity by 4.7×10^{-24} ft/s. This will move the earth one inch in five trillion centuries. (The reader should not worry about the accumulated effects of shooting on the earth's trajectory, because air friction and the final impact produce equal and opposite forces which exactly counteract the velocity increment of the earth.) If the shooter is suspended free of the earth, his much smaller mass will be accelerated to a speed of four inches per second.

The previous paragraph discussed the effects of a man firing a .30 caliber rifle while standing on the earth and while suspended in the air. The effects are small but different. Larger caliber guns require much larger and stronger supports than a rifleman to keep the gun coupled to the earth. Our problem is greater yet. Propellant Emplaced Anchors (PEAs) comprise a system of large anchors for semipermanent mooring of ships. The anchors are shot into the sea floor to increase their effective lifetimes and their load capacities. There are four load ranges from 10,000 pounds to 300,000 pounds. Depending on their holding capacities and the type of sea floor they are intended for, the anchors' weights range from 160 pounds to 6,800 pounds, and their required velocities range from 360 to 520 ft/s. These are massive "bullets." Projecting the largest of these anchors from a reasonable gun tube requires projective forces (and therefore recoil forces) of over 1.5 million pounds. There is no practical way to tie the PEA gun barrel directly to the

earth during normal use. Therefore, the handling of the large recoil forces generated by PEAs is a significant problem. It is the topic of this report.

It will be necessary to develop a quantitative understanding of the problem before looking at potential solutions. Figure 2 shows the general layout of an unsupported launch tube, propellant charge, and anchor. It also shows the principal forces acting on anchor and launch tube. The net force acting on the anchor and the launcher is:

A-I-1 $$F_i = (P-P_a)\,A - F_f - \tfrac{1}{2}\rho\, A_i\, C_{di}\, U_i^2$$

where subscript i = designates anchor when i = 1 and launch tube when i = 2

F_i = net force (pounds)

P = gas pressure in launch tube (psf)

P_a = ambient pressure (psfa)

A = cross-sectional area of launch tube and piston (sq ft)

F_f = friction force between anchor piston and launch tube wall (pounds)

ρ = density of seawater (slugs/cu ft)

A_i = maximum cross sectional area of anchor or launch tube (sq ft)

C_{di} = drag coefficient (dimensionless)

U_i = velocity (ft/s)

The instantaneous accelerations of the anchor and launch tube are:

A-I-2 $$\dot{U}_i = a_i = F_i/M_i$$

where $\dot{U}_i = a_i$ = acceleration (ft/s^2)

M_i = mass (including virtual mass) (slugs)

The instantaneous velocities are:

A-I-3 $$U_i = \int_0^t a_i d\tau$$

where t = time (sec)

The distances travelled by the anchor and launch tube are given by:

A-I-4 $$x_i = \int_0^t U_i \, d\tau$$

where x_i = the distance traveled by the anchor or the launch tube (ft)

All one must do to compute the trajectories of the anchor and launch tube is to integrate equations A-I-3 and 4 for i = 1 and 2 simultaneously until

A-I-5 $$x_1 + x_2 = L$$

where L = the effective length of the launch tube (ft).

One must know the various coefficients and boundary conditions before the equations can be integrated. In addition, the pressure must be known as a function of time and/or the sum x_1+x_2. In the detailed calculations the pressure will be given as a differential equation involving pressure, time, and x_1+x_2.

For approximate calculations, one may neglect the F_f and the fluid dynamic drag. Further, the pressure may be assumed constant because that gives the best performance and because it is nearly achievable. With these simplifications, the final velocity of the anchor is

A-I-6 $$U_{1\ final} = \sqrt{\frac{2(P-P_a)AL}{M_1} \quad \frac{M_2}{M_1+M_2}}$$

The first term in the radical on the right-hand side of Equation A-I-6 is the square of the final anchor velocity that would result if the launcher were firmly attached to a very large, effectively infinite, mass. The second term on the right-hand side is a correction term for the case where the launcher is attached to a finite mass. The product of these two terms is the final anchor velocity when the mass of the launch tube is significant and free to move.

The correction term is always less than one. It increases as M_2 increases relative to M_1. Equation A-I-6 shows that U_1 final can be increased by increasing P, A, L, and/or M_2 and/or by decreasing M_1.

II. CURRENT PEA DESIGNS: To increase the effective mass of the launcher without increasing its physical mass, the original designers added reaction vessels to increase the virtual mass of the launcher. Virtual mass is the mass of the water that gets accelerated along with an object. The virtual mass is added to the physical mass of the object being accelerated, but only while it is being accelerated. The quantity of the virtual mass is proportional to the maximum cross-sectional area of the object, taken perpendicular to the direction of acceleration. The proportionality constant is determined by the shape of the object. Figure 3 shows the present PEA design and how the virtual mass is increased by adding the reaction vessels. This is a good shape for increasing the virtual mass as well as increasing the drag. While this design achieves the required anchor velocity, it is large, heavy, and awkward. Furthermore, the reaction vessels on the larger anchor launchers occasionally break. The rest of this paper is a description, analysis, and evaluation of several new concepts for launchers that do not need reaction vessels.

III. PROPOSED NEW APPROACHES TO LAUNCHER MASS REDUCTION: While the solutions developed in this paper also apply to the smaller PEAs, the main emphasis is placed on the 300 KIP PEA because of its size, weight, and handling problems. The purpose of these new approaches is to accelerate the anchor to the required velocity without making the launcher large, heavy, awkward, or prone to failure. All of the new approaches have one feature in common. Instead of reducing the effect of the recoil force by adding mass to the launcher, they all neutralize the recoil force with another source of thrust.

The three basic options are shown in Figure 4. The first option is the archetype for the rest. It is a scaled-up recoilless rifle with the anchor as a projectile. Conceptually, it is a PEA with an enlarged gas generator and a rocket nozzle venting to the rear. The thrust from the rocket nozzle can be tailored to exactly neutralize the recoil force. This makes M_2 effectively infinite. Since there is no recoil displacement to reduce the efficiency of

the launcher, the pressure may be reduced. This, in turn, allows the launch tube to be thinner and lighter. On the negative side is the need for a much larger and more expensive gas generator.

The second option is derived from the first by the observation that the rocket thrust required to overcome the recoil force is exactly equal to that required to propel the anchor. Therefore, why not eliminate the launch tube and propel the anchor directly by the rocket's thrust? The launch tube is eliminated completely. There are other less obvious advantages to this option. The thrust duration is not limited by the length of a launch tube, because there is no launch tube. The thrust duration is only limited by the standoff, distance between the sea floor, and the launch position. The rocket thrust can be reduced because the required thrust is inversely proportional to this standoff distance. The principal disadvantage is that the mass of the rocket motor must be added to M_1, the mass of the anchor. This requires an even larger and more expensive vented gas generator than that required for the recoilless launcher.

The third option is similar to the first in overall concept. Instead of using an ordinary rocket which vents the propellant gas, this concept uses a water jet. Gas from a gas generator forces water out the nozzle. The principal advantage of the water jet is a smaller (by half), simpler, and unvented gas generator. An unvented gas generator avoids all of the problems of the large vented gas generators.

B. RECOILLESS OPTION

While all of the options considered in this report are effectively recoilless, the term will be reserved for the combination of a launch tube with a rocket which neutralizes the recoil force. The recoilless option is a direct copy of the recoilless rifle first used extensively in the Korean War. This original recoilless rifle eliminates the need for heavy gun mounts by eliminating the recoil. This permits light artillery to be fired from light tripod mounts. These light tripods are required only to support the weight of the gun and to facilitate aiming; they do not have to absorb any recoil forces.

I. RECOILLESS RIFLE TECHNOLOGY APPLIED TO PEAs

As shown in Figure 4, a recoilless anchor launcher has a single combustion chamber which produces gas to drive the anchor via the piston and to power the rocket. The piston area and the nozzle throat area are preset so that the two forces acting on the launch tube are equal and opposite, thus keeping the launcher stationary. As before, the force accelerating the anchor is:

B-I-1 $$F_1 = (P - P_a) A - F_f - \tfrac{1}{2} \rho A_1 C_{d1} U_1^2$$

The recoil force is:

B-I-2 $$F_2 = (P - P_a) A - F_f$$

The thrust from the rocket must equal F_2 if the launcher is to be kept stationary. The rocket thrust, F_3, is:

B-I-3 $$F_3 = P A_t C_f$$

where A_t = throat area of the nozzle (sq ft)

C_f = thrust coefficient (dimensionless)

Equating equations B-I-2 and 3, and solving for A_t gives:

B-I-4 $$A_t = \frac{A (P-Pa)-F_f}{C_f P}$$

P_a is small with respect to P, and F_f is fairly small. Therefore, A_t can be estimated by:

B-I-5 $$A_t = \frac{A}{C_f}$$

The net force on the launch tube for the recoilless option is:

B-I-6 $$F_{2T} = (P - P_a) A - F_f - P A_t C_f - \tfrac{1}{2} \rho A_2 C_{D2} U_2^2$$

To do a detailed calculation of the performance expected from any given set of parameters, one must substitute equations B-I-1 and 6 into equations A-I-2 and integrate as in equations A-I-3 and 4 to the boundary condition expressed in equation A-I-5. To do this one needs an equation (algebraic or differential) for P.

If one assumes that P is constant and F_{2T} is nearly zero, then the equations can be solved analytically. The general equations for the anchor velocity and displacement are:

B-I-7 $\quad U_1 = U_{1\infty} \tanh(t/\tau)$ and

B-I-8 $\quad x_1 = U_{1\infty} \tau \log_e(\cosh(t/\tau))$

where $U_{1\infty}$ = terminal velocity of the anchor if the driving force were maintained indefinitely. When U_1 equ $U_{1\infty}$ then F_1 in equation B-I-1 = 0.

B-I-9
$$U_{1\infty} = \sqrt{\frac{(P-P_a)\,A - F_f}{\tfrac{1}{2}\,\rho\,A_1\,C_{d1}}}$$

B-I-10 $\quad \tau$ = a characteristic time

$$\tau = \frac{M_1\,U_{1\infty}}{(P-P_a)A-F_f}$$

The time, t, can be eliminated from equations B-I-7 and 8 to give U_1 as a function of x.

B-I-11
$$U_1 = U_{1\infty}\sqrt{1 - \exp\,(-2x/U_{1\infty}\tau)}$$

where $\quad \exp\,(\beta) = e^{\beta}$

The final velocity can be calculated by substituting L for x in equation B-I-11.

These equations are useful for evaluating proposed systems and for comparing different types of systems, but they don't describe the gas generator necessary to provide the constant thrust. No real gas generator provides a perfectly constant pressure; therefore, more detailed calculations are needed

to give accurate results. These detailed calculations will give answers for a real gas generator, but more important, they will be a powerful design tool for the development of the gas generator.

II. INTERIOR BALLISTICS: This technology area gives the means to calculate the changing interior pressure, P, and the means to design an effective propellant system. The first equation needed is the equation of state, which relates the pressure, volume, mass, temperature, and molecular weight of the gas. The ideal gas equation is usually used for more moderate pressure, but the high pressures used in the PEAs need an equation of state such as the modified van der Waals equation of state.

B-II-1 $$P\left(V - b\frac{m}{MW}\right) = \frac{m}{MW}RT$$

b = covolume, a measure of the finite volume of the gas molecules

MW = molecular weight of the gas (slugs/slug-mole)

V = volume available to the gas (cu ft)

R = universal gas constant (49,709 ft-lb/slug mole-^{0}R)

T = absolute temperature of the gas (^{0}R)

m = mass of gas (slugs)

MW and b are parameters whose values depend on the composition of the gas; R is a universal constant; P, V, m, and T are variables. To calculate instantaneous values of P, it is necessary to know the two parameters, MW and b, the universal gas constant, R, and the variables V, m, and T. The remainder of this section covers the calculations of these variables.

The process starts with the burning of the propellant to produce the gas. The surface of the propellant regresses everywhere perpendicular to the burning surface. Figure 5 shows a propellant grain with a single perforation (monoperf), and Figure 6 shows a grain with seven perforations (seven perf). Figures 7 and 8 show a rocket propellant grain of a design that might be appropriate to a recoilless or direct rocket PEA. The drawings show how the grains regress as they burn; the grain is shown unburned and partially

burned. The following equations give the surfaces of the three types of grains as functions of their original dimensions and the burned distance, z. These functions are needed to calculate the rate of gas production.

B-II-2 $$S_m = \pi\,(OD_o + ID_o)\,\{\tfrac{1}{2}(OD_o - ID_o) + H_o - 4z\}$$

where S_m = burning surface of one monoperf propellant grain (sq. ft.)

OD_o = original outside diameter of grains (ft.)

ID_o = original inside diameter of perforation (ft)

H_o = original length of grain (ft)

z = distance burned, perpendicular to grain's surface (ft)

This monoperf grain is totally consumed whenever $z = H_o/2$ or $z = (OD_o - ID_o)/4$, whichever comes first. The equation for the seven perf grain is:

B-II-3 $$S_s = \pi\,\{\tfrac{1}{2}(OD_o - 7ID_o) + H_o(OD_o + 7ID)_o + 2z(6H_o - 2OD_o - 14ID_o) - 36z^2\}$$

where S_s = burning surface of one seven perf propellant grain (sq ft)

This equation for S_s, is valid while $z > \dfrac{OD_o - 3ID_o}{8}$. When z reaches this limit, 7/8 of the grain is burned. The remaining part of the grain burns in two modes. It takes about six equations to calculate the surface of these afterburns. These equations are not shown here, but they are in the computer program listed in Appendix A. The equation for the rocket propellant grain is:

B-II-4 $$S_r = (H_o + 2w - 4z)\,\{16\,h_o - 8\,ID_o\phi + \pi\,(ID_o + 8w + 2z)\} - 2\pi(3w - z)(w + z) + 4ID_o\{\phi(ID_o + 4w) - 2w\cos\phi\}$$

S_r = instantaneous surface of a rocket type grain (sq ft)

h_o = length of straight sides of the spokes (feet)

w = web of propellant grain (feet)

ϕ = arcsine $(2w/ID_o)$ (radians)

The next item needed is the propellant's regression rate, $\dot{z}$.

B-II-5 $\dot{z} = B P^n$

where B = burning rate coefficient (ft/s psf^{-n})

n = burning rate exponent (dimensionless)

Both B and n are determined by the composition of the propellant. The overall burning rate $\dot{m}_b$ is given by:

B-II-6 $\dot{m}_b = N S \rho_p \dot{z}$

where N = number of propellant grains (dimensionless)

S = S_m, S_s, or S_r as appropriate (sq ft)

ρ_p = density of the propellant (slugs/cu ft)

In both the recoilless and the rocket launched PEAs, most of the propellant gas goes out the nozzle. The equation for the exhaust mass flow rate is:

B-II-7 $\dot{m}_e = P A_t C_e$

where A_t = area of the throat of the nozzle (sq ft)

C_e = discharge coefficient of propellant gas (slugs/pound)

Typical values for the discharge coefficient are .0002 slugs/pound-seconds. The net rate of accumulation of propellant gas is:

B-II-8 $\dot{m} = N S \rho_p B P^n - P A_t C_e$

where $m(0) = \frac{P(0)\ V(0)\ MW}{b\ P(0) + R\ T(0)}$

The next item to be calculated is the volume, V, available to the gas. This volume comes from three sources; the initial or free volume, V_f; the rate of increase of volume due to motion of the piston which is equal to $(U_1 + U_2) A$; and the burning of the propellant grains. The gas volume, V, is given as a derivative with respect to time. The boundary condition at time = 0 is V_f.

B-II-9 $\dot{V} = (U_1 + U_2)A + N\, S\, B\, P^n$

and $V(0) = V_f$ = initial volume available to gas (cu ft)

The next state function to be calculated is the temperature, T. The changes in temperature will be rather small in all of the configurations being considered here, because the propellants burn to produce gas at constant temperature. This constant flame temperature and the high burning rates tend to maintain the temperature nearly constant. The combination of a high throughput and a short action time means that heat transfer is minimal. The only significant heat loss comes from the expansion work done by the gas. The time derivative of the temperature is:

B-II-10 $\dot{T} = (T_f - T)\ \dot{m}_b/m - P\ \dot{V}_u/(c_p\ J\ m)$

c_p = specific heat (Btu/slug-^{0}R)

J = mechanical equivalent of heat (778.3 ft-lb/Btu)

$c_p\ J = \frac{\gamma}{\gamma-1}\ \frac{R}{MW}$

γ = ratio of specific heats (dimensionless)

$T(0) = T_f$

$\dot{V}_u = (U_1 + U_2)A$

Substitute Equations B-I-1 and 6 into Equation A-I-2 gives:

B-II-11 $\dot{U}_1 = \{(P - P_a)\ A - F_f - \frac{1}{2}\rho\ A_1\ C_{d1}\ U_1^2\}/M_1$

B-II-12 $\dot{U}_2 = \{(P - P_a)\ A - F_f - \frac{1}{2}\rho\ A_2\ C_{d2}\ U_2^2 - P\ A_t\ C_f\}/M_2$

Taking the derivitive of equation A-I-4 gives:

B-II-13 $\dot{x}_1 = U_1$

B-II-14 $\dot{x}_2 = U_2$

All of the equations for the recoilless launcher are finally assembled. The first step in calculating the performance of a specific recoilless design is to determine all of the parameters and boundary conditions. The next step is to select an appropriate burning surface equation; equation B-II-2, 3, or 4, or some other equation if a different grain is used. The burning surface and equation of state, equation B-II-1, are auxiliary equations. Equations B-II-8 through B-II-14 are all first order differential equations that must be integrated simultaneously until the final boundary condition is met, ($x_1 + x_2 = L$). Because of the mixed nature of these equations, it will be necessary to use numerical techniques to integrate them. If the reader is planning to write a computer program to carry out these integrations, he should be aware of several conventions used in the derivation of the equations: The sign of U_1 is positive when it is going forward, the desired direction. Similarly, the sign of U_2 is considered positive when it is going rearward, its natural direction of motion. U_2 might become negative if the rocket thrust is higher than the recoil force. It is extremely unlikely that U_1 will ever become negative, but the possibility that U_2 can become negative may cause a problem in equation B-II-12. All of the terms in this equation have intrinsic directions indicated by their signs. The fluid drag term ($\frac{1}{2} \rho C_{di} A_i U_i^2$)is always opposite in sign to the velocity U_2. The equations as given are correct so long as the velocity, U_2, is positive. This can be handled in a computer program by multipying this term by a function SIGNUM(U_2). This function has a value of +1 or -1 as as U_2 is positive or negative.

Appendix A is a copy of a computer program like the one just described, and a run showing a typical set of results. This program was encoded several months before the detailed analysis shown in this report. This explains the difference between them. For example, the program uses the ideal gas equation of state instead of the modified van der Waals equation of state. Also the program does not have a term for fluid dynamic drag on the launcher, because the launcher velocity is intended to be so low that the drag is insignificant.

The calculations show that the anchor can be accelerated to 300 ft/s by a recoilless device operating at 20,000 psi. The propellant charge assumed in this calculation consisted of 115 seven perf grains (Figure 6). This is not

the usual way to fuel a solid propellant rocket. Most solid propellant rocket motors have one or two grains that are nearly as large as the motor. The grains are also of such a shape that they stay in place with a very high reliability. This is not the case with relatively small grains. They can be blown through the large nozzles required by the PEAs. It is not clear that the techniques for grain retention that work in the much smaller recoilless rifles will work in the PEA combustion chambers. If this potential problem becomes serious, then it will be necessary to use rocket-like propellant grains as described in Figure 7, if they can be made to sustain the high acceleration load. It seems clear that the development of the propellant assembly would be an expensive and chancy undertaking.

C. DIRECT ROCKET

The recoilless PEA launcher system described in the previous section appears to be a theoretically workable solution to the problems involved in launching large PEAs, if the propellant problems can be solved. Also, it is rather sophisticated. This level of sophistication is accepted in light artillery because it can give high velocity and accuracy without recoil in a hand held weapon. PEAs are not hand held and they do not require high accuracy. High velocity and adequate accuracy can be achieved with unguided direct rocket propulsion, but the direct rocket shares the recoilless PEA's propellant problems. With the direct rocket, the gun tube and piston are eliminated.

1. DESCRIPTION OF DIRECT ROCKET PROPELLED PEA:

A direct rocket powered PEA is shown in Figure 4. The rocket motor is attached directly to the anchor. The thrust from the rocket motor, less the fluid dynamic drag on the assembly, accelerates the anchor and the rocket motor. The analysis of the forces is simpler than for the original PEA system and the recoilless system, because the whole apparatus moves as a unit.

The "up front" advantages of the direct rocket propelled PEAs are the reduced weight and complexity resulting from the elimination of the launch tube and piston. There is another, less obvious, advantage to the direct rocket PEAs. The duration of the thrust is not tied to the barrel length, because there is no barrel. The rocket can fire for a somewhat longer time at a lower thrust level. If desirable, the thrust can be continued through

penetration of the sea floor. The direct rocket PEAs also have several disadvantages relative to the original and the recoilless PEAs. In the original and recoilless systems, only the anchor and the piston are accelerated forward. In the direct rocket PEA, everthing is accelerated forward. This substantially increases the drag and the propelled mass, thus requiring an increased thrust. Another disadvantage of the direct rocket is that the propellant grain(s) is exposed to the same high acceleration and gas flow as the anchor (250 g's). This could cause the propellant to break up and the motor to fail or rupture.

II. ANALYSIS OF DIRECT ROCKET PEA:

This analysis is less wordy because it closely parallels the analysis of the recoilless PEA. It starts with the forces on the body. The subscript, 3, will be used to distinguish variables relating to the direct rocket PEA. The net force on the body is:

C-II-1 $$F_3 = P\ A_t\ C_f - \tfrac{1}{2} \rho\ U_3^2\ A_3\ C_{d3}$$

All of the terms have been defined earlier. The terminal velocity, $U_{3\infty}$, is the velocity at which $F_3 = 0$. It can be calculated by setting F_3 equal to zero in Equation C-II-1, and solving for the terminal velocity.

C-II-2 $$U_{3\infty} = \sqrt{\frac{P\ A_t\ C_f}{\tfrac{1}{2} \rho\ A_3\ C_{d3}}}$$

The rate of change of the mass of the vehicle is:

C-II-3 $$\dot{M}_3 = -P\ A_t\ C_e$$

The initial mass of the vehicle, including propellant, is $M_3(0)$. The velocity of the vehicle is given by the differential equation:

C-II-4 $$\dot{U}_3 = F_3/M_3$$

The position of the vehicle is given by the differential equation:

C-II-5 $$\dot{x}_3 = U_3$$

The initial values of U_3 and X_3 are zero. All that is necessary to integrate the equation is a way to calculate the instantaneous value of P. This can be done with most of the same equations used for the recoilless PEA. Equations B-II-1 to B-II-8 can be used as they are. The rate of change of the gas volume is different because there is no piston.

C-II-6 $$\dot{V}_3 = N\ S\ B\ P^n$$

Equation B-II-10 is not needed because the temperature remains constant.

As with the recoilless PEA calculations, the first step is to get values for the boundary conditions and parameters. A burning surface equation must be selected from B-II-2, 3, or 4; or some combinations of them;or some other equation as needed. The equation of state, equation B-II-1, is needed, and the differential equations B-II-8, C-II-4, 5, and 6 are needed. Again, as with the recoilless PEA, these equations must be solved by numerical techniques. An example program is shown in Appendix B along with a sample calculation.

The differential equations can be solved in closed form if the pressure is constant. The velocity as a function of time is:

C-II-7 $$U_3 = U_{3\infty} \tanh \left[- \frac{C}{U_{3\infty}} \log_e \{1 - \frac{PA_tC_e}{M_o} t\} \right]$$

where $C = C_f/C_e$ = velocity of rocket exhaust (ft/s)

D. WATER JET PEAs

While explaining the details of the assignment to the author, the sponsors mentioned an unusual propulsion scheme proposed at Port Hueneme. That proposal was for a gas driven water jet to neutralize the recoil force. Our understanding was that the gas was to be supplied from compressed gas (air) cylinders. To get the needed results would require nearly 50,000 standard

cubic feet of gas compressed to 40,000 psi. Half of this compressed gas would have to be transferred to the water chamber in 40 milliseconds. This would require a very impressive valve. While it seems very unlikely that the job can be done with compressed gas, the picture is quite different if the driving gas is generated by burning a charge of gun propellant. Instead of nearly two tons of very high pressure air, not to mention the tankage, the job can be done with only 200 pounds of gun propellant.

I. WATER JET PEA DESCRIPTION

Figure 4 gives a conceptual drawing of a water jet PEA. A water jet PEA, operating at 20,000 psi[1] (2,880,000 psf), will have a six foot long launch tube with an inside diameter of ten inches (.8333 ft). This would be connected to the end of water tube that is 5.5 feet long and a 2.12 foot inside diameter. Its shape will be cylindrical with hemispherical ends. The free end of the 5.5 foot diameter tube is terminated with a convergent nozzle with an exit area of .25 square feet (ID = .564 ft). The propellant charge and the igniter are stored in the end of the water tube near the launch tube; the drive piston fits into the .833 foot diameter tube; and the seawater goes into the 2.12 foot inside diameter water tube. The water tube is dry during storage and handling. It fills with seawater while being lowered into the sea.

The propellant charge is ignited when the assembly is lowered to its deployment depth. The burning propellant causes the pressure to rise quickly to a constant level of about 20,000 psi internal. The high pressure causes the water to accelerate and stream out of the nozzle. After a few milliseconds, the exit velocity stabilizes at about 1,700 feet per second. Near the end of the water expulsion, there is another acceleration as the nozzle empties. Figure 10 is a graph of the water velocity as a function of time. The higher velocity trace represents the velocity of the water leaving the nozzle. The lower velocity trace represents the velocity of the gas-water interface.

II. ANALYSIS OF THE WATER JET PEA

The equations needed to calculate the performance of the water jet PEA are the same as those used for the recoilless PEA, with one exception. That

[1] A later section will cover water jet PEAs operating at other pressures.

exception is equation B-I-3, which gives the thrust from the rocket. The thrust from the water jet is:

D-II-1
$$F_5 = \rho A_t U_5^2 (1 - A_t/A_{wt}) + \rho A_{wt} (L - x) \frac{dU_4}{dt}$$

where U_5 = exit velocity of water (ft/s)

U_4 = velocity of water at interface with drive gas (ft/s)

L = length of the water tube (feet)

The definition of the terms is given pictorially in Figure 9. The detailed calculation is somewhat lengthy and complex, and it will not be derived here. The derivation, along with a computer model and sample problem, is given in Appendix C. If one assumes a constant gas pressure of 20,000 psi, the following events occur in sequence. Figure 10 should be referenced during the explanation. Initially, the water is at rest, but it starts to accelerate as the pressure is applied. The initial acceleration of the main body of water is about 240,000 ft/s^2 but it drops to zero in about four milliseconds. The average acceleration over the four milliseconds is 42,500 ft/s^2. The initial high acceleration is caused by the high pressure gradient across the constant area length of the water column. As the velocity increases, the pressure gradient across the constant area length decreases until the acceleration reaches zero. At that time, all of the pressure gradient is across the nozzle where the speed increases by a factor of ten. A particle of water in the constant area section is traveling at about 170 ft/s, so long as it remains in the constant area section. When it reaches the nozzle it accelerates in one millisecond to 1,700 ft/s, an acceleration of 1,530,000 ft/s^2.

Without detail, the operating sequence is: Four milliseconds accelerating the main body of water to its steady state speed of 170 ft/s; 35 milliseconds at the steady speed of 170 ft/s; and one millisecond of very high acceleration as the nozzle empties. During this whole process, the water leaving the nozzle is traveling ten times faster than the water in the main body. During the main steady portion, the exit velocity is 1,700 ft/s. The exit velocity can easily be calculated for the steady flow by equating the total heads at the inlet and the exit of the nozzle along with the continuity equation.

D-II-2 $$P + \tfrac{1}{2}\rho U_4^2 = P_a + \tfrac{1}{2}\rho U_5^2$$

where U_4 = velocity of the gas-water interface (ft/s)

U_5 = water velocity at exit from nozzle (ft/s)

The continuity equation is:

D-II-3 $$\rho A_{wt} U_4 = \rho A_t U_5$$

where A_{wt} = cross sectional area of straight portion of the water tube (sq ft)

Combining the equations gives:

D-II-4 $$\rho U_5^2 = \frac{2(P-P_a)}{1-(A_t/A_{wt})^2}$$

Combining this result with the steady state form of equation D-II-1 gives:

D-II-5 $$F_5 = \frac{2 A_t (P-P_a)}{1+(A_t/A_{wt})}$$

If the forces are balanced so that the launcher remains stationary, then the motion of the anchor will be described by equations B-I-7 to 10. The following equation must be satisfied to have the forces balanced.

D-II-6 $$A_t = A_{wt}\frac{(P-P_a)A - F_f}{(P-P_a)(2A_{wt}-A) + F_f}$$

Since F_f is small compared to $(P-P_a)A$, a good approximation for is

D-II-7 $$A_t = \frac{A_{wt} A}{2A_{wt} - A}.$$

Assuming the same 2,880,000 psf (20,000 psi) that was used for the recoilless and direct rocket examples, the water jet exit velocity is 1,704 ft/s. With a nozzle throat area A_t, of .25 sq ft, the thrust would be 1.5×10^6

pounds. The mass flow out the nozzle will be 852 slugs/s (27,400 pounds/s) for .04 seconds. The total mass of water is 34 slugs (weighing 1,100 pounds). To hold this much water, the internal volume of the water tube must be 17 cu. ft. For example, the tube could have an inside diameter of 2.12 feet and a length of 5.5 feet. The launcher also requires the piston tube which is six feet long and ten inches in inside diameter.

E. COMPARISON OF THE APPROACHES

After having read this enthusiastic description of these several ways of reliably launching large PEAs, it is time to examine and compare them critically. They will be compared on the basis of weight, size, and probability of successful development. Finally, a recommendation will be made as to which option should be developed.

I. SIZE AND WEIGHT COMPARISON:

The size and weight comparisons are taken together because they are based on the same parameters. The launch tube comparison will be done first, because it is common to the recoilless and the water jet options. The key relationship for the launch tubes is the requirement that they deliver a force of 1.44×10^6 pounds over a stroke of six feet. Therefore, the inside diameter of the launch tube is

E-I-1 $$ID_b = \sqrt{\frac{4 F_i}{\pi P}}$$

Note that inside diameter of the launch tube is given in feet and the pressure is given in psf. Figure 11 is a graph of the launch tube inside diameter as a function of pressure. In order to determine the wall thickness, one needs the yield strength of the material of construction. Because the pressures will be high, it will be necessary to use thick wall equations for cylinders to calculate the wall thickness. This equation is:

E-I-2 $$P = S_y \frac{\Omega^2 - 1}{2\,\Omega^2} \quad \text{or} \quad \Omega = \sqrt{\frac{S_y}{S_y - 2P}}$$

where S_y = yield strength of material (same units as pressure)

and $\Omega = OD_b / ID_b$

Since $OD_b = ID_b + 2t$

where t = wall thickness.

Equation E-I-2 can be rearranged to

E-I-3 $$t = \frac{ID_b}{2}\left[\sqrt{\frac{S_y}{S_y - 2P}} - 1\right]$$

The weight of the steel tube launch is given by

E-I-4 $$W_b = \rho_b L_b \frac{\pi}{4}\left(OD^2{}_b - ID^2{}_b\right)$$

where L_b = length of the launch tube cylinder

ρ_b = density of structural material of launch tube.

OD_b = outside diameter of launch tube (ft)

ID_b = inside diameter of launch tube (ft)

One must be careful to match all of the units in these equations. If Equation E-I-1 and 2 are substituted into Equation E-I-4 and simplified, one gets

E-I-5 $$W_b = \rho_b L_b \frac{2 F_i}{S_y - 2P}$$

Figure 12 is a plot of W_b as a function of S_y at several values of P with L fixed at six feet (72 inches). Examining Figure 12 shows that the weight decreases as the yield stress increases and as the pressure decreases. If one reduces the weight of the launch tube by decreasing the pressure, one must increase the inside diameter according to Equation E-I-1. At this time it is not clear what, if any, negative effects are related to large launch tube diameters.

The launch tube is the smaller of the two main components of the proposed PEAs, and the calculation of its size and weight is straightforward. The size and weight of the water tube for the water jet PEA can also be calculated by straightforward analysis. Unfortunately, the rocket motors of the recoilless and the direct rockets are not so simply handled. They require huge thrusts ranging from 1.5 to 3.0 million pounds and an extremely short burn time of .040 seconds. The volumes of main stream service rockets are proportional to their total impulse, I_t. The approximate volume of a main stream rocket can be calculated by:

E-I-6 $$V \approx 6.2 \times 10^{-5} I_t$$

where V = volume of a mainstream rocket (cu ft)

Since the total impulse required for the PEA rocket motors range from 58,000 to 80,000 pound-seconds, the estimated volume ranges from 3.6 to 5.0 cubic feet. However, it would be totally impossible to make a rocket of this volume deliver 1.5 to 3.0 million pounds of thrust. To provide the very large thrust would require two or three hundred thousand square inches of burning surface. The propellant would have to be divided into many small pieces, and they must be supported in a dispersed array to allow room for 6,800 pounds per second of gas to flow through the array to the nozzle. This would cause a large increase in the volume of the PEA rockets over that predicted from their total impulse. It is difficult to predict how large the volume increase would have to be, because the PEA rockets would be far out of the main stream of r..ket motors.

The water jet must produce a thrust, F5, of 1.44×10^6 pounds of thrust for .040 seconds. Starting with Bernoulli's Equation, Equation D-II-2, and the thrust Equation D-II-5, one can derive an equation for the mass flow of water coming out from the nozzle. This equation follows:

E-I-7 $$\dot{m}_w = F_5 \sqrt{\frac{\rho_{w/2}}{P - P_a - F_5/A_{wt}}}$$ see Equation E-I-8

Since $$\dot{m}_w \times t = m_w \text{ and } F_3\, t = I_{t3}$$

We can multiply both sides by t, and calculate the weight of the water.

E-I-8 $$m_w = I_{5t} \sqrt{\frac{\rho_{w/2}}{P - P_a - F_5/A_{wt}}}$$

Dividing both sides by ρ_w gives the volume of the water that will be ejected during the launching.

E-I-9 $$V_w = \frac{I_{5t}}{\sqrt{2 \rho_w (P - P_a - F_5/A_{wt})}}$$

The dimensions of the water tube can now be calculated. First, the inside diameter, ID_3 , must be selected. The water tubes will have cylinders with hemispherical caps. Given this shape and the internal volume, one can calculate the length, L_3 .

E-I-10 $$L_3 = \frac{4 V_w}{\pi ID_3^2} + ID_3/3$$

Figure 13 is a plot of water tube length as a function of ID_3 and pressure. Because the walls are moderately thick, it will be necessary to use the thick wall equations. The thick wall equation for cylinders was given earlier, Equation E-I-2 and 3. The equation for spheres is very similar

E-I-11 $$P = S_y \frac{\mu^3 - 1}{1.5 \mu^3}$$

Since μ is the ratio of the outside diameter to the inside diameter, the outside diameter of the spheres is

E-I-12 $$OD_{sph} = ID_3 \sqrt[3]{\frac{S_y}{S_y - 1.5P}}$$

The weight of the water tube is

E-I-13 $$W_{wt} = \rho_{wt} \left[\frac{\pi}{4} (L_3 - ID_3) (OD^2_{cyl} - ID_3^2) + \frac{\pi}{6} (OD^3_{sph} - ID_3^3) \right]$$

Using Equations E-I-2, 12, and 13, one can calculate the weight of the water tube. Besides the equations, one needs the weight density of the material, the length and inside diameter, the pressure, and the yield stress of the material.

E-I-14 $$W_{wt} = \rho_{wt} \frac{\pi}{4} P \, ID_3^2 \left[\frac{2(L_3 - ID_3)}{S_y - 2P} + \frac{ID_3}{S_y - 1.5P} \right]$$

The most likely material for the water tube and launch tube is steel. It has a weight density of 492 pounds per cubic foot. Composite materials, such as fibre glass-epoxy would permit lower weights.

Appendix D is a copy of a BASIC computer program that computes all of the dimensions and weights of the launch tube and water tube. The program computes all of these values for a matrix of pressure, inside diameter, and yield stress of material of construction. The limits and increments of the matrix are specified by the user. Besides the program, Appendix D includes several output sheets each of which lists the results for one inside diameter, a range of pressure, and a range of yield stresses. Figure 11 is a graph of the launch tube inside diameter as a function of pressure; Figure 12 is graph of of the launch tube weigth as a function of yield stress and pressure. Figure 13 is a graph of the length of the water tube as a function of its inside diameter and the working pressure. Figures 14 to 26 are plots showing the weight of the whole assembly (launch tube and water tube). Each figure has a family of curves, one for each value of the yield stress. One set of graphs, Figures 14 to 21 plot the system weight versus the pressure. There is one graph for each of the eight inside diameters considered. Figures 22 to 26 graph the system weight versus the inside diameter. There are five graphs, one for each pressure considered. With the aid of these graphs, one can select a configuration which most closely meets the needs of the users. One must keep in mind that although these analyses are very thorough, they are "first cuts." One shortcoming is the fact that the sizes given do not include space for the propellant.

F. CONCLUSIONS AND RECOMMENDATIONS

Upon first examination, all three of the PEA launchers considered in this paper look workable. However, an examination of the requirements for the rocket motors needed for the recoilless and the direct rocket PEAs, shows a huge rocket engineering job. The recoilless PEA requires a total impulse of 57,600 pound-seconds. A typical service rocket with that total impulse would have about 250 pounds of propellant and have thrusts ranging from 6,000 to 36,000 pounds. The highest thrust of these rockets is nearly two orders of magnitude too low for the PEA application. One of the few service rockets which have a thrust near the 1.44 million pounds required is the TITAN III C, which is ten feet in diameter and 85 feet long--somewhat larger than desired. To bridge this gap, the propellant must be divided into many small pieces so that there will be sufficient burning surface. Some very strong means must be devised to hold the propellant in the combustion chamber while three tons per second of dense gas are flowing from the combustion chamber to and through the nozzle. The drag on the propellant grains from this enormous flow would rip the grains loose and out the nozzle before they were burned. The highly divided grains and the distributed flow area required would make such a rocket motor much larger than other 57,600 pound-second rocket motors. The development and production costs for such rocket motors would be too high for this program.

The problems associated with the two high thrust rocket motors derive from the combination of many small grains of propellant, such as gun propellant, with a high flow through the bed of propellant grains and out a nozzle. The water jet PEA also requires highly divided, gun like propellant, but the combustion chamber is not vented. The burning propellant is always enclosed in a rapidly growing volume defined by the anchor piston, the water and launcher tubes, and the gas-water interface. Therefore, the propellant grains do not have to be restrained. All that is needed is a frangible waterproof container that can keep the propellant dry during the deployment. The large scale swaging equipment needed to make the water tube and launch tube are available, and production costs are moderate.

The conclusion of this study is that the water jet PEA is clearly the best choice. Experimental development of this system should be started as soon as possible.

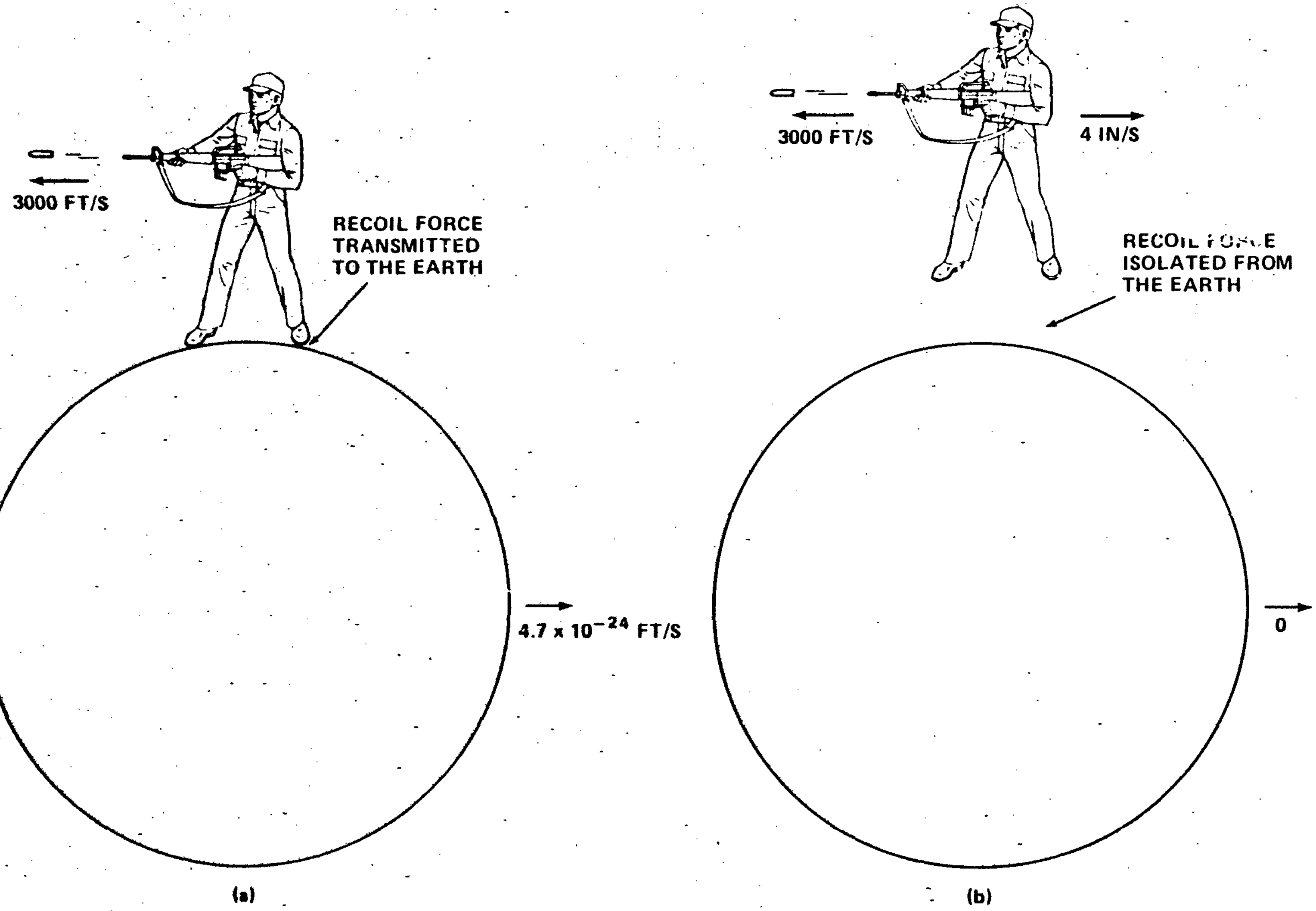


FIGURE 1. COMPARISON OF EFFECT FROM A PERSON FIRING A .30 CALIBER RIFLE WHILE STANDING ON THE EARTH (a) AND SUSPENDED ABOVE THE EARTH (b)

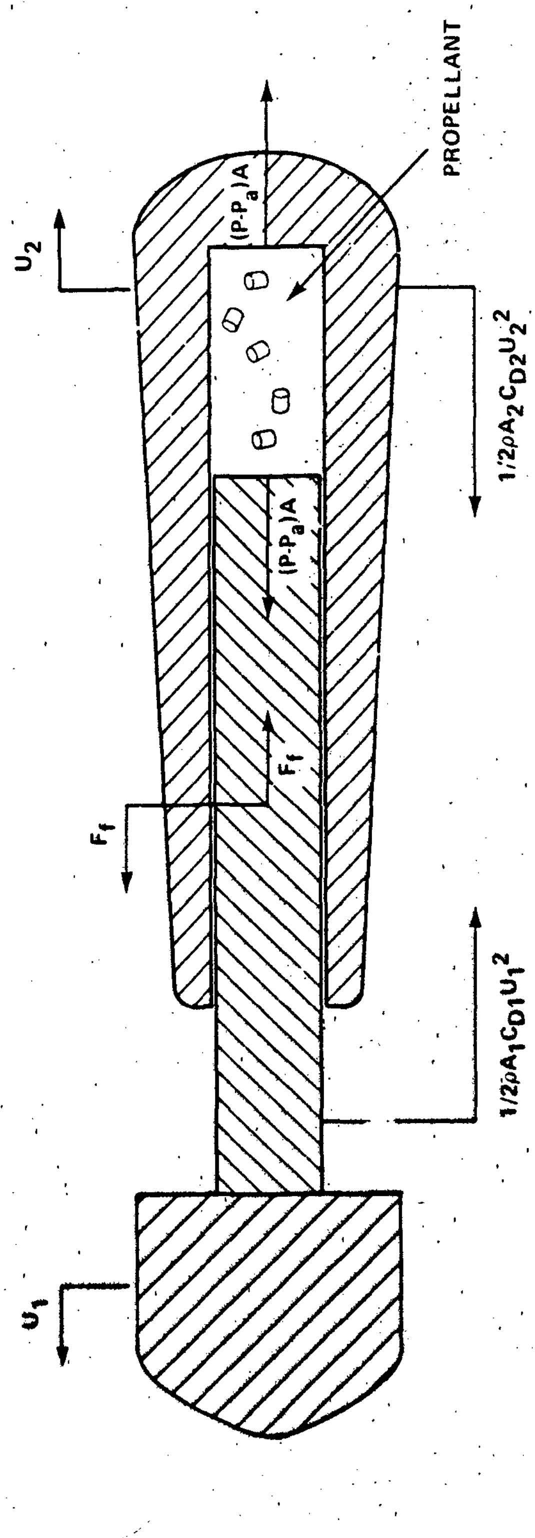


FIGURE 2. A CUTAWAY DRAWING OF A SIMPLIFIED PEA LAUNCHER WITH NO VIRTUAL MASS AUGMENTER

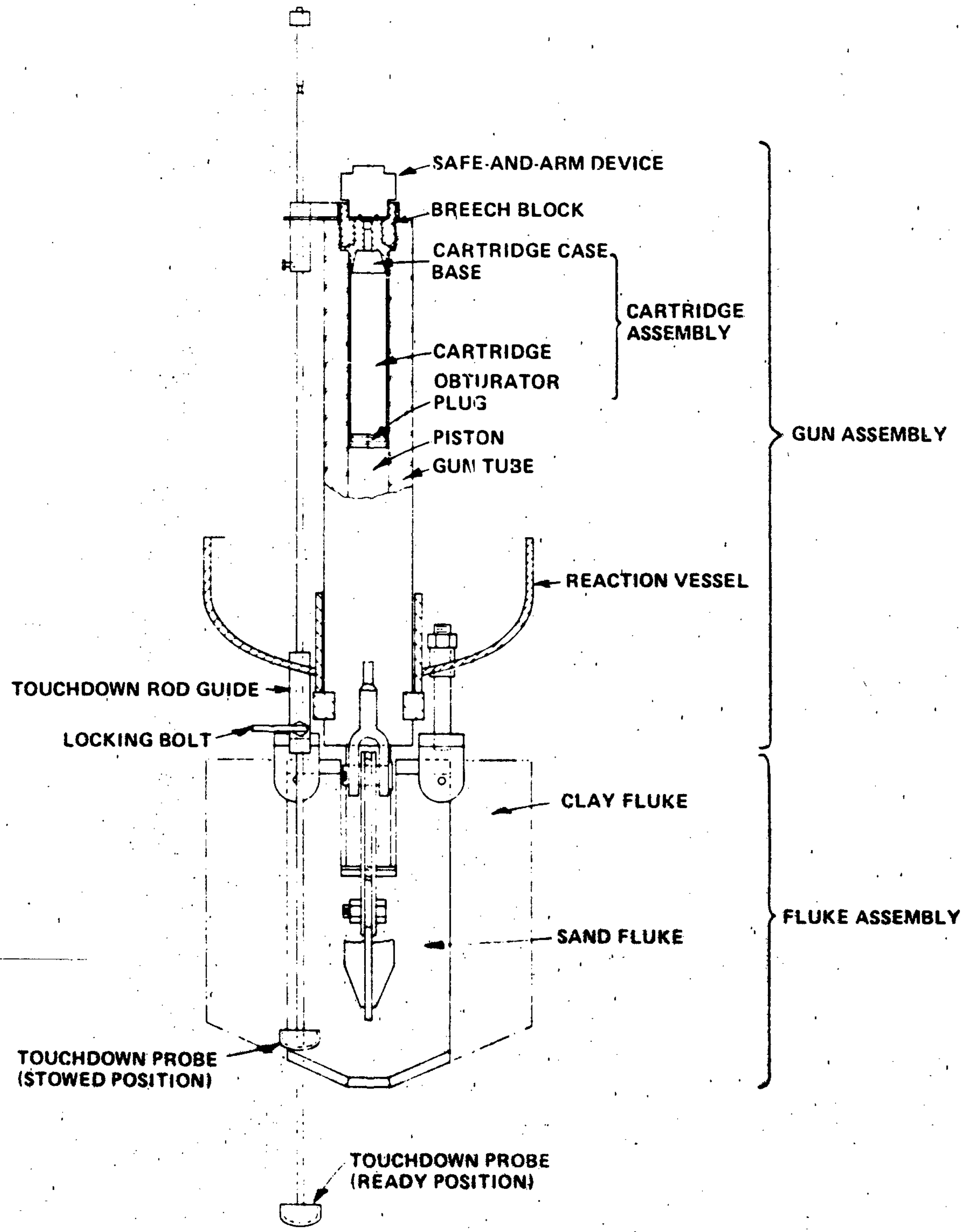
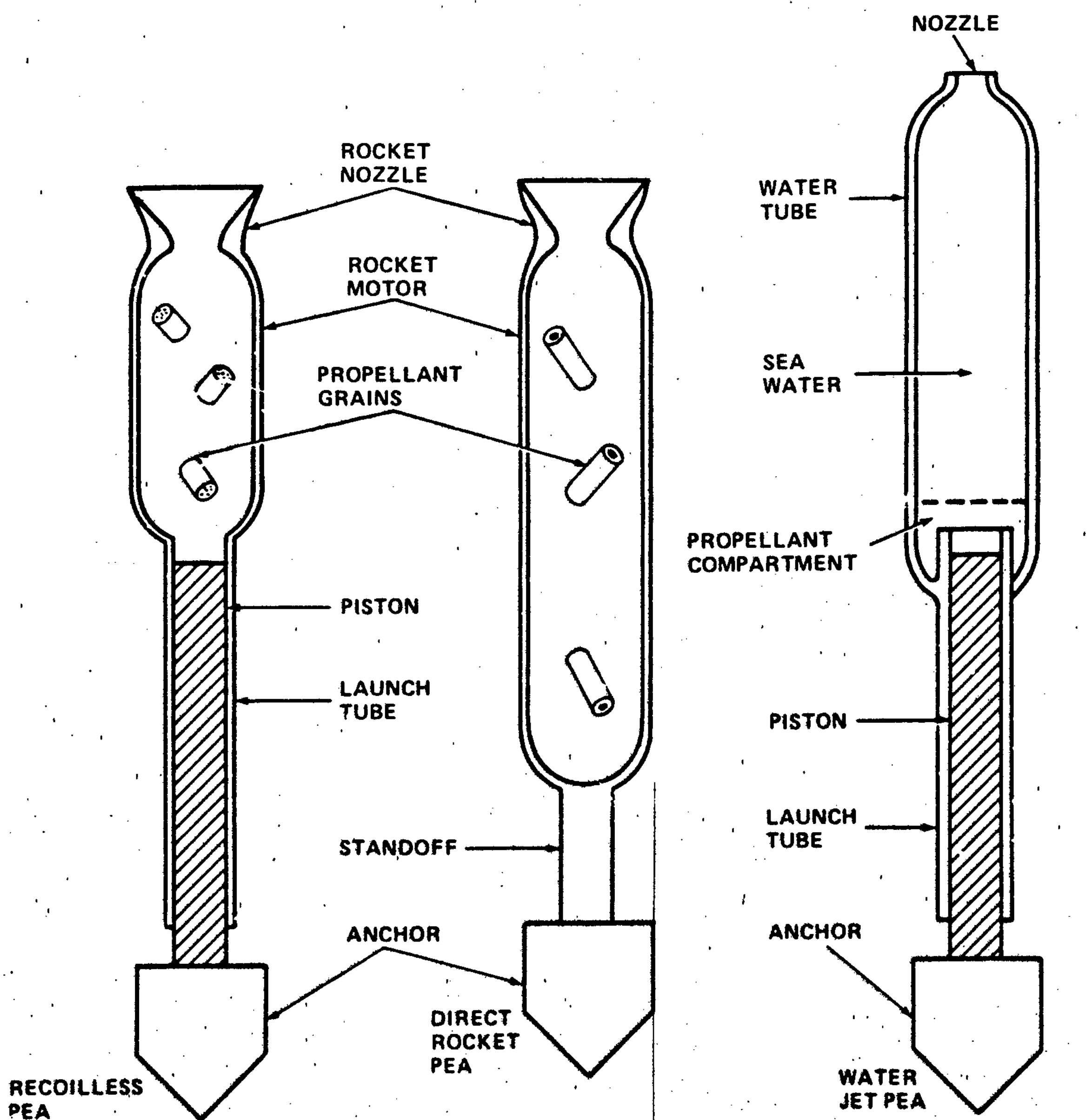
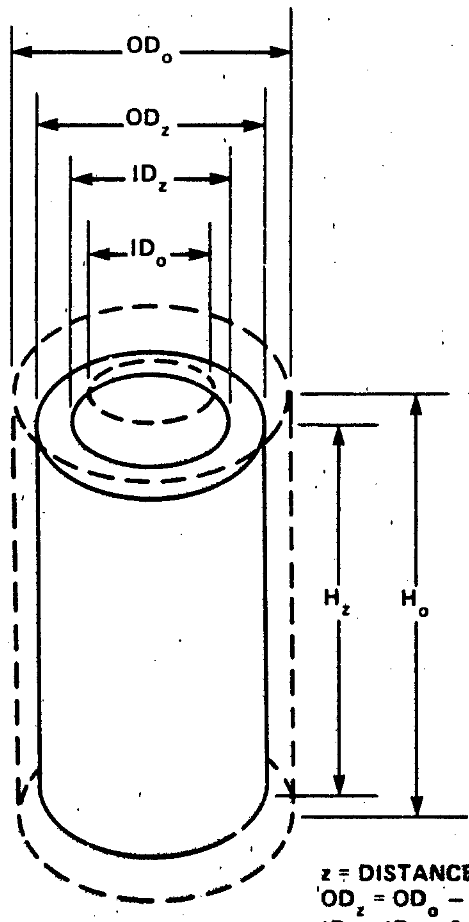


FIGURE 3. PARTIAL CUTAWAY DRAWING OF A SMALL (10 KIP) PROPELLANT EMPLACED ANCHOR



IGURE 4. CONCEPTUAL DRAWINGS FOR ALL THREE RECOILLESS PEA'S INVESTIGATED IN THIS REPORT



z = DISTANCE BURNED
$OD_z = OD_o - 2z$
$ID_z = ID_o + 2z$
$H_z = H_o - 2z$

SURFACE PER GRAIN = $\pi(OD_o + ID_o)(OD_o - ID_o/2 + H_o - 4z)$
WHILE $z \leq (OD_o - ID_o)/4$

FIGURE 5. THE SURFACE OF A MONOPERFORATED GRAIN AS IT BURNS AWAY

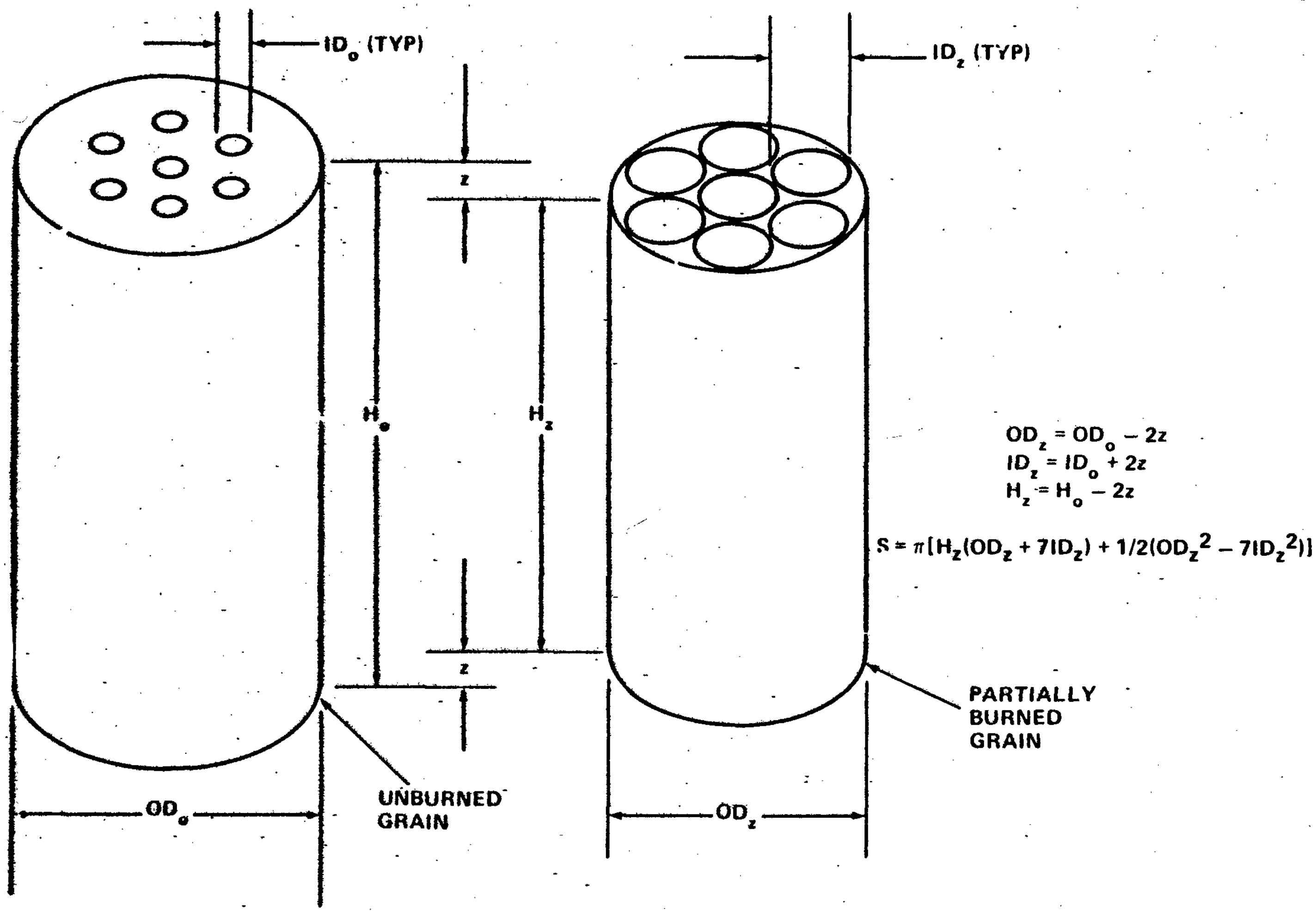


FIGURE 6. SEVEN PERF GRAIN SHOWN UNBURNED AND NEAR FIRST BURNOUT

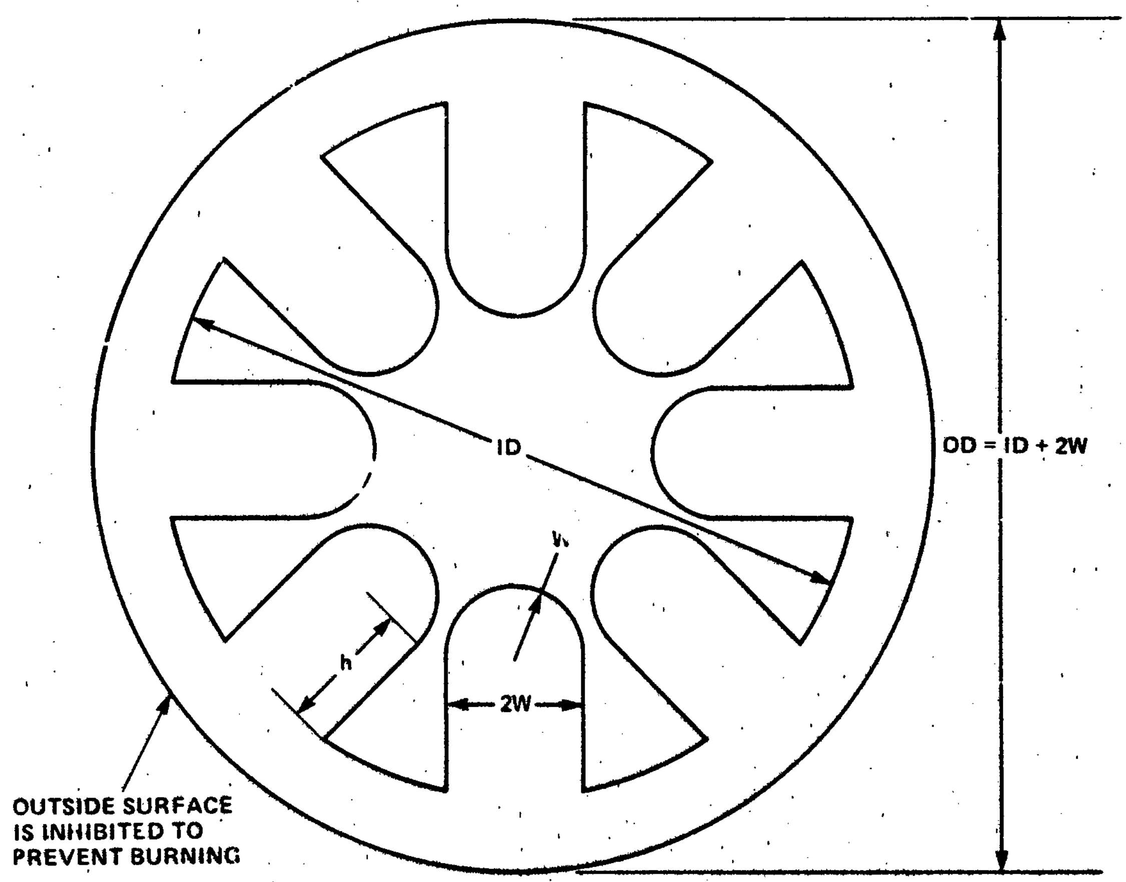


FIGURE 7. CROSS SECTIONAL VIEW OF A PROPELLANT GRAIN APPROPRIATE TO A ROCKET OR RECOILLESS PEA. FIGURE 8 SHOWS THE DETAILS OF BURNING

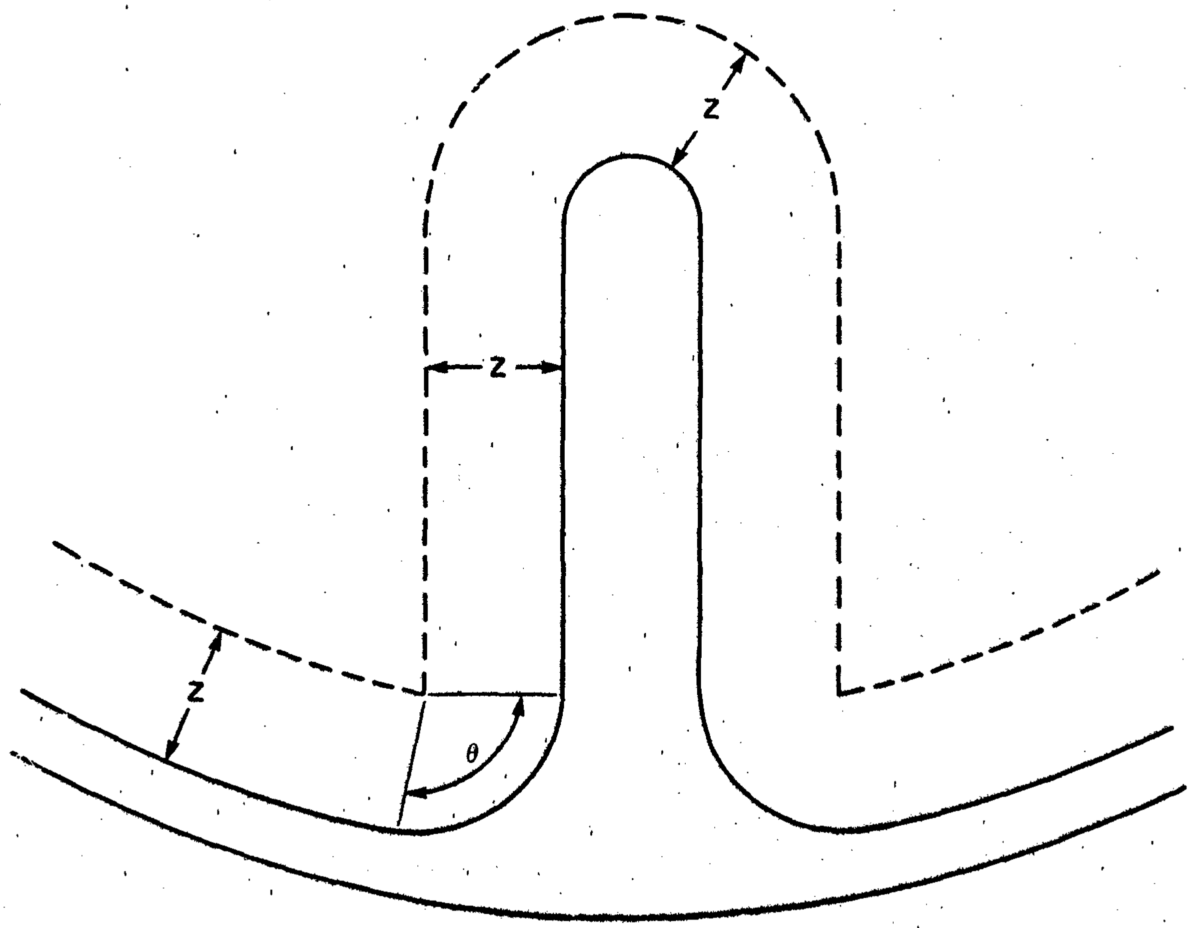


FIGURE 8. A DETAIL FROM FIGURE 7, SHOWING THE BURNING PATH. (DASHED LINES INDICATE ORIGINAL SHAPE AND SOLID LINES THE INSTANTANEOUS SHAPE)

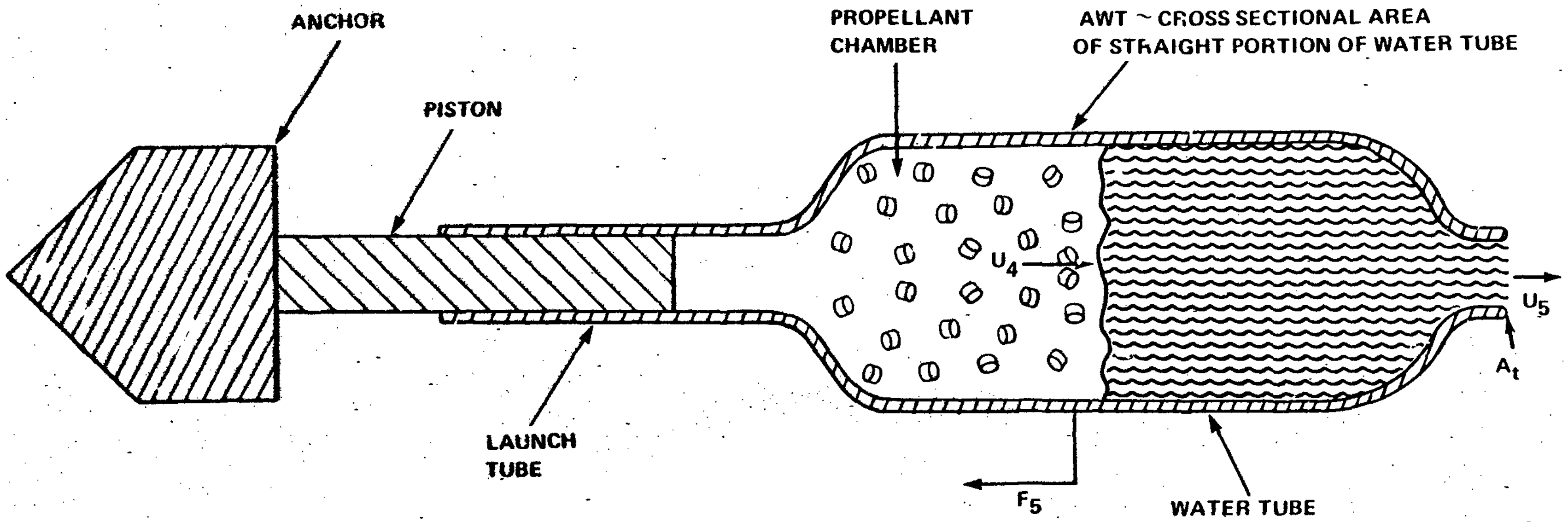


FIGURE 9. DRAWING OF WATER JET PEA SHOWING GENERATION OF FORCE

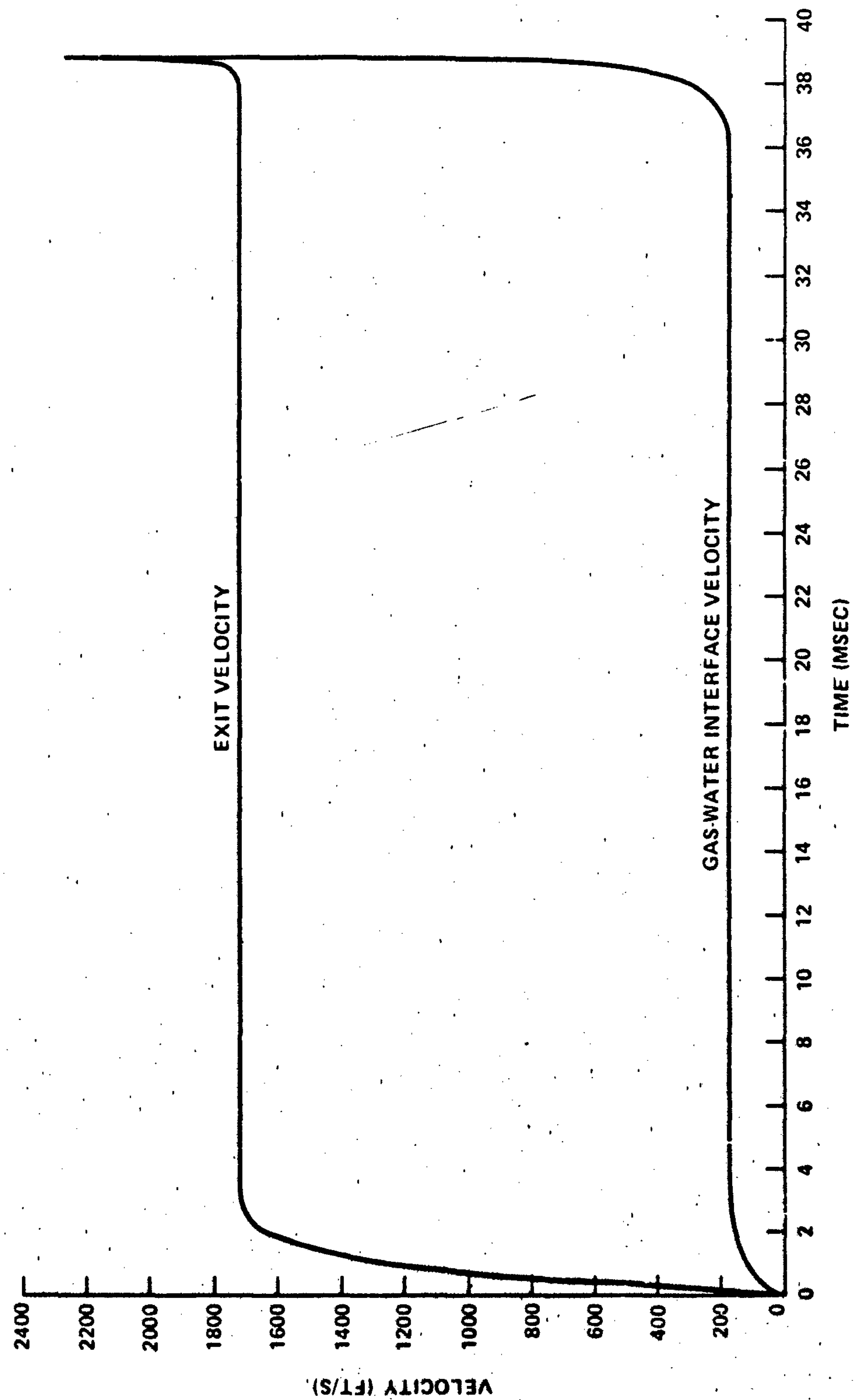


FIGURE 10. WATER VELOCITY AT EXIT AND AT GAS-WATER INTERFACE AS A FUNCTION OF TIME. (PRESSURE IS ASSUMED TO BE CONSTANT AT 20,000 PSI)

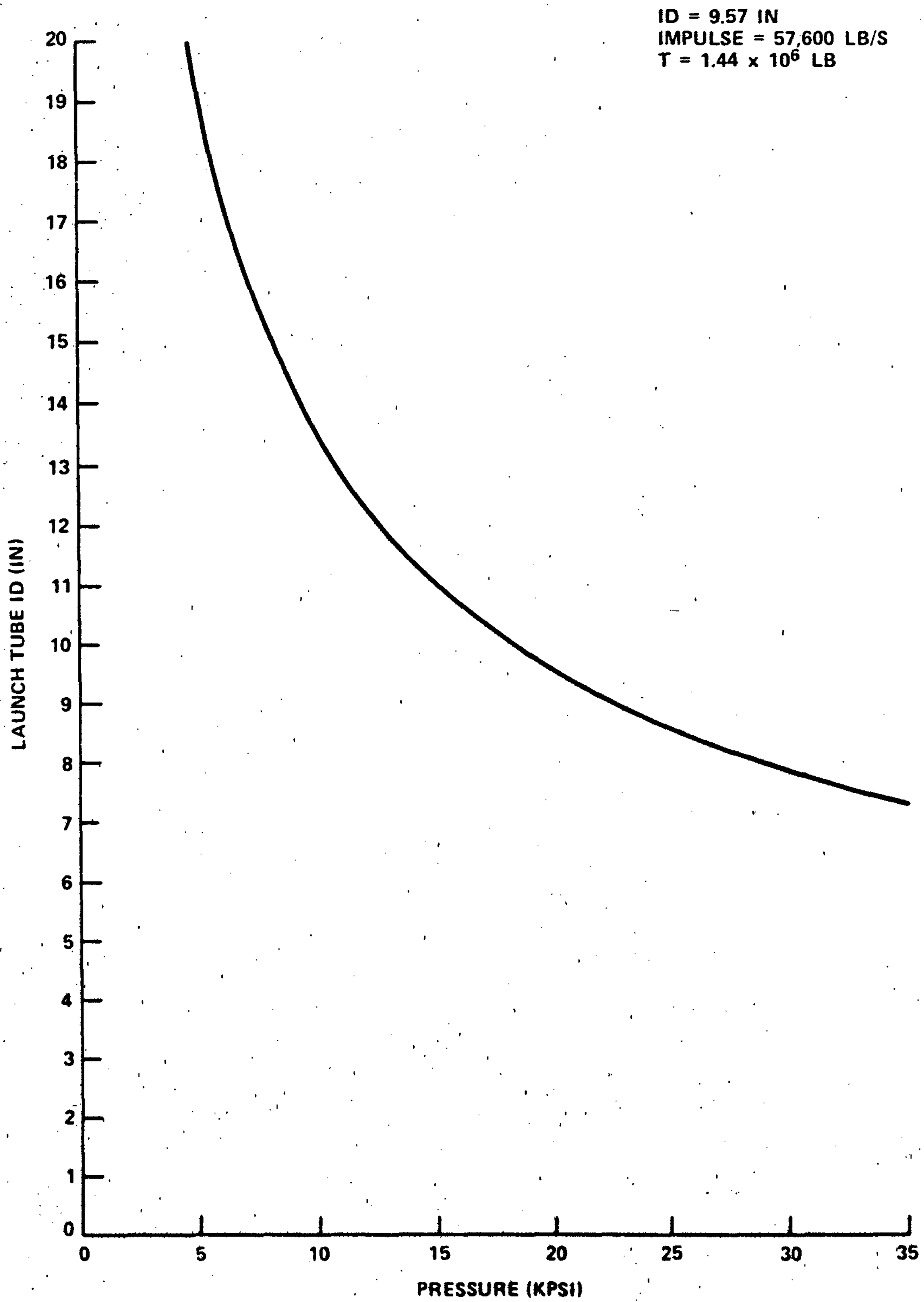


FIGURE 11. REQUIRED INSIDE DIAMETER OF LAUNCH TUBE AS A FUNCTION OF DRIVE PRESSURE

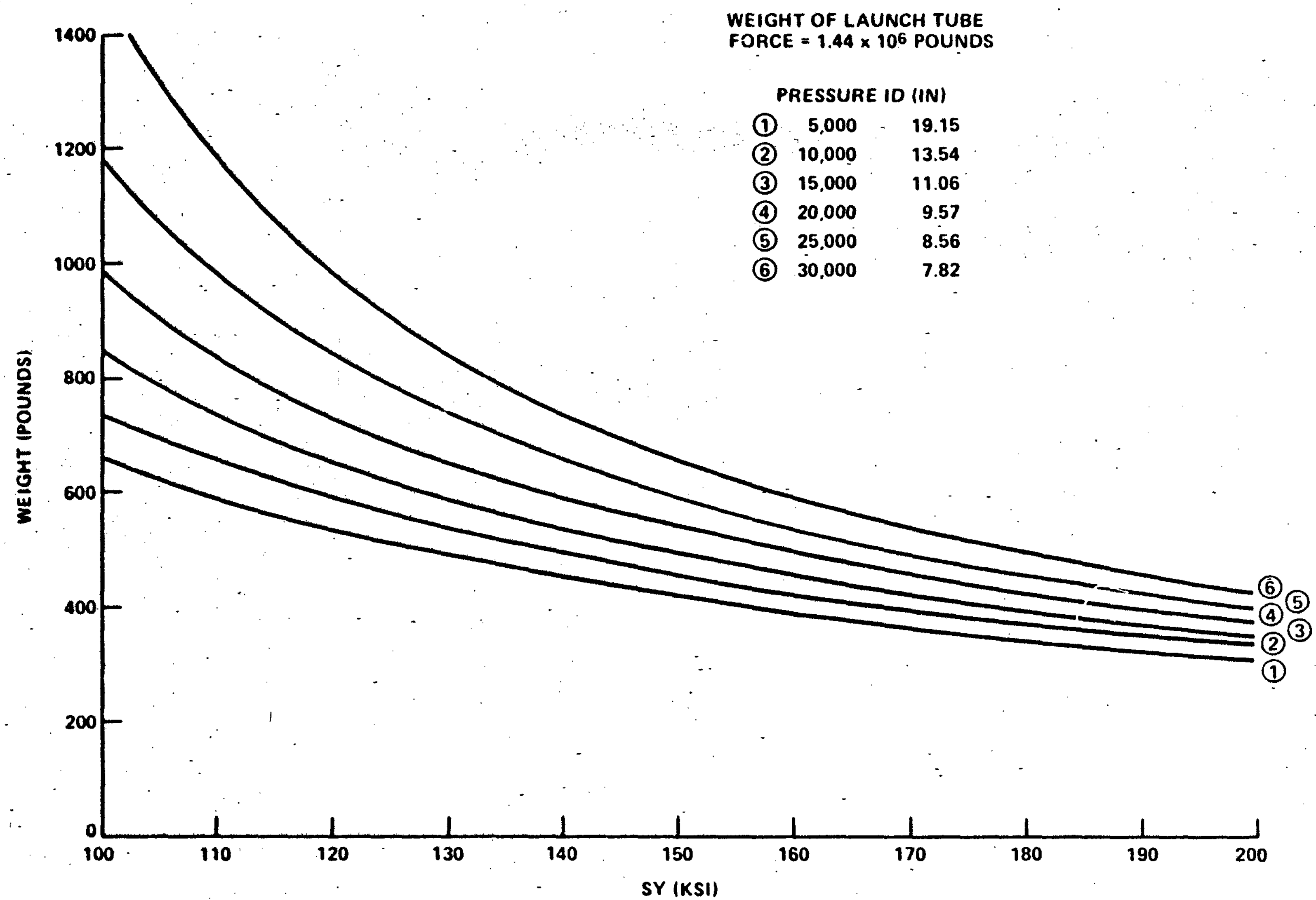


FIGURE 12. WEIGHT OF LAUNCH TUBE AS A FUNCTION OF PRESSURE AND YIELD STRESS OF MATERIAL (ASSUMED LENGTH IS SIX FEET AND THRUST IS 1.44 x 10^6 POUNDS)

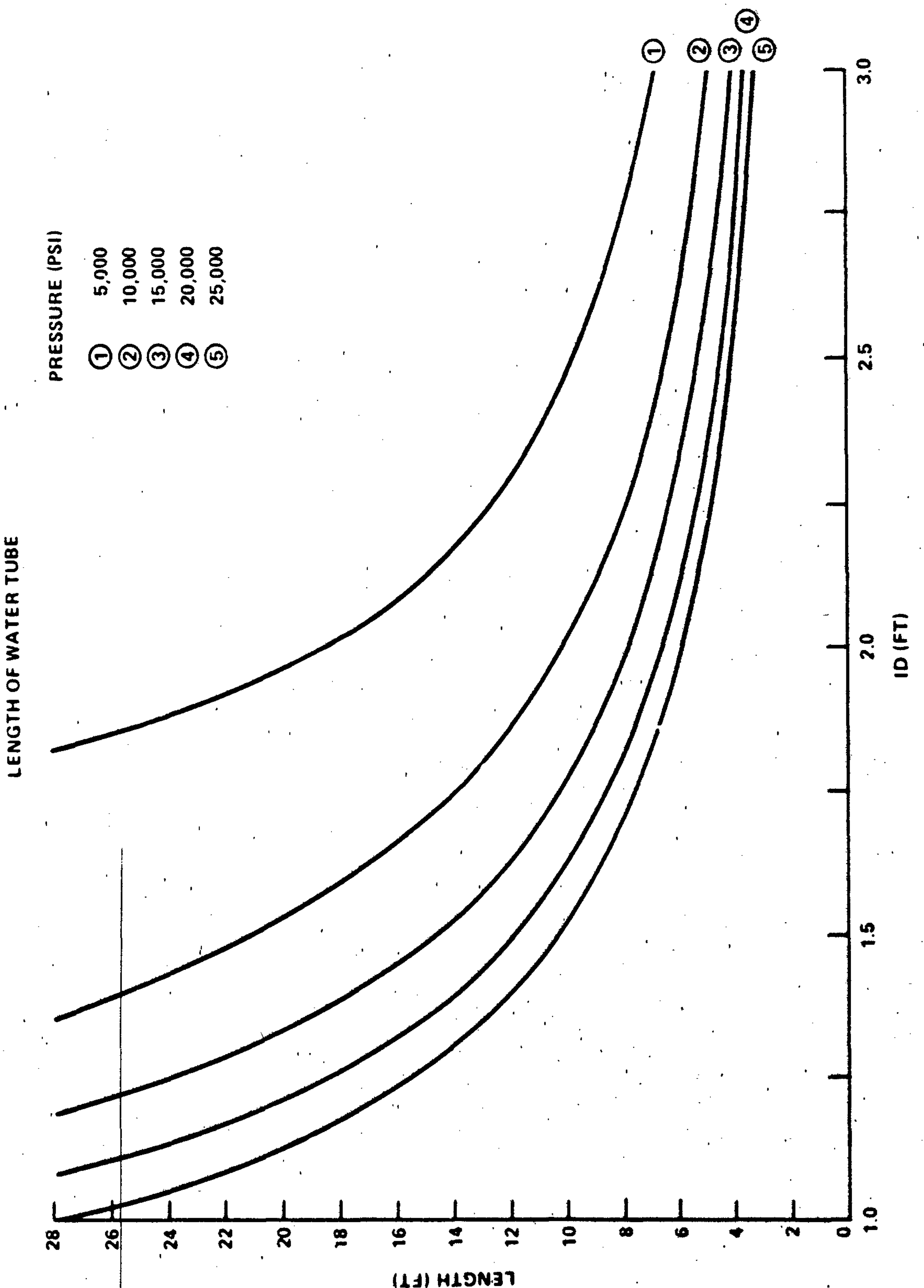


FIGURE 13. LENGTH OF WATER TUBE AS A FUNCTION OF PRESSURE AND WATER TUBE INSIDE DIAMETER

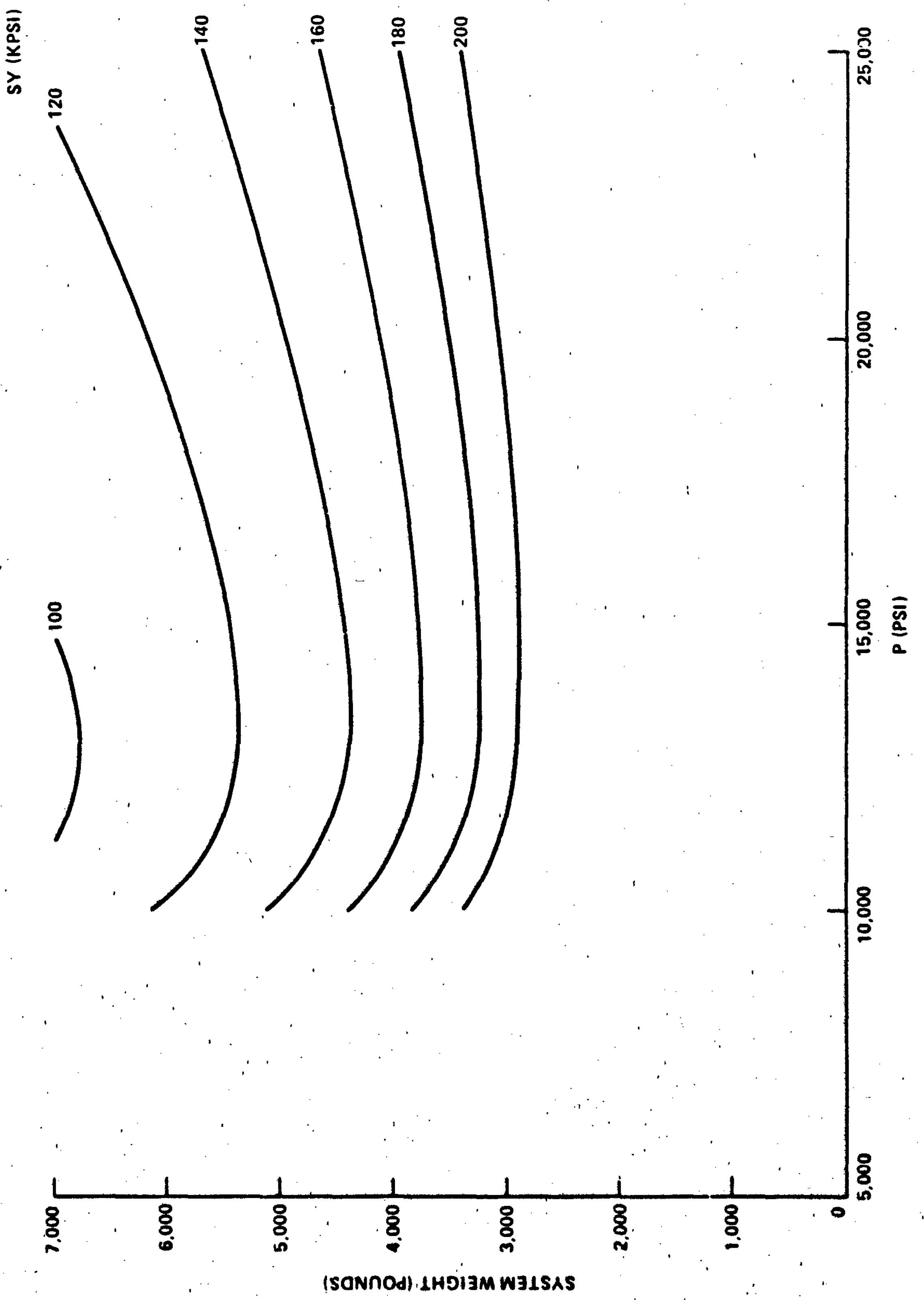


FIGURE 14: PLOT OF WATER JET TOTAL SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 1.25 FEET

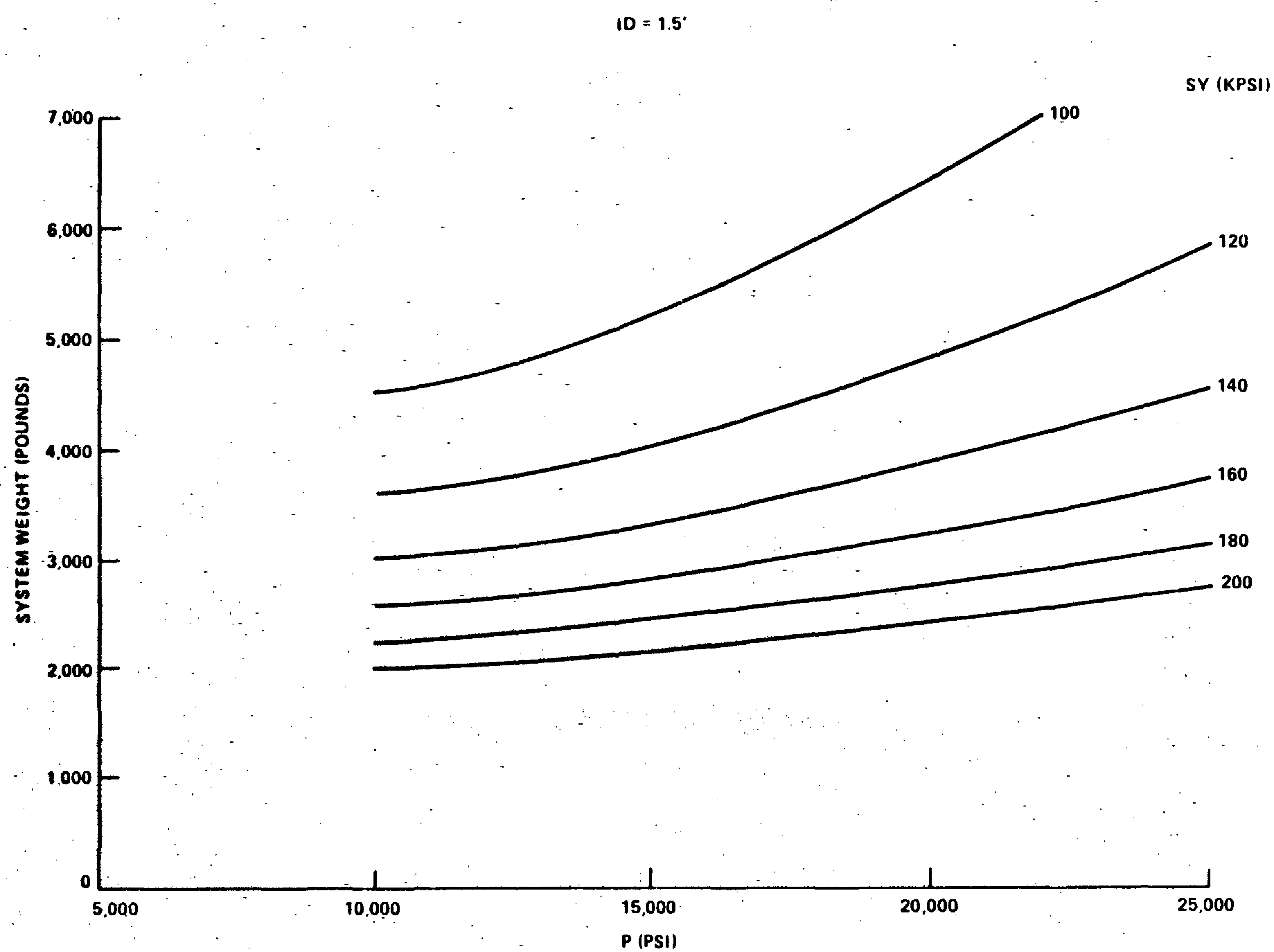


FIGURE 15. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 1.5 FEET

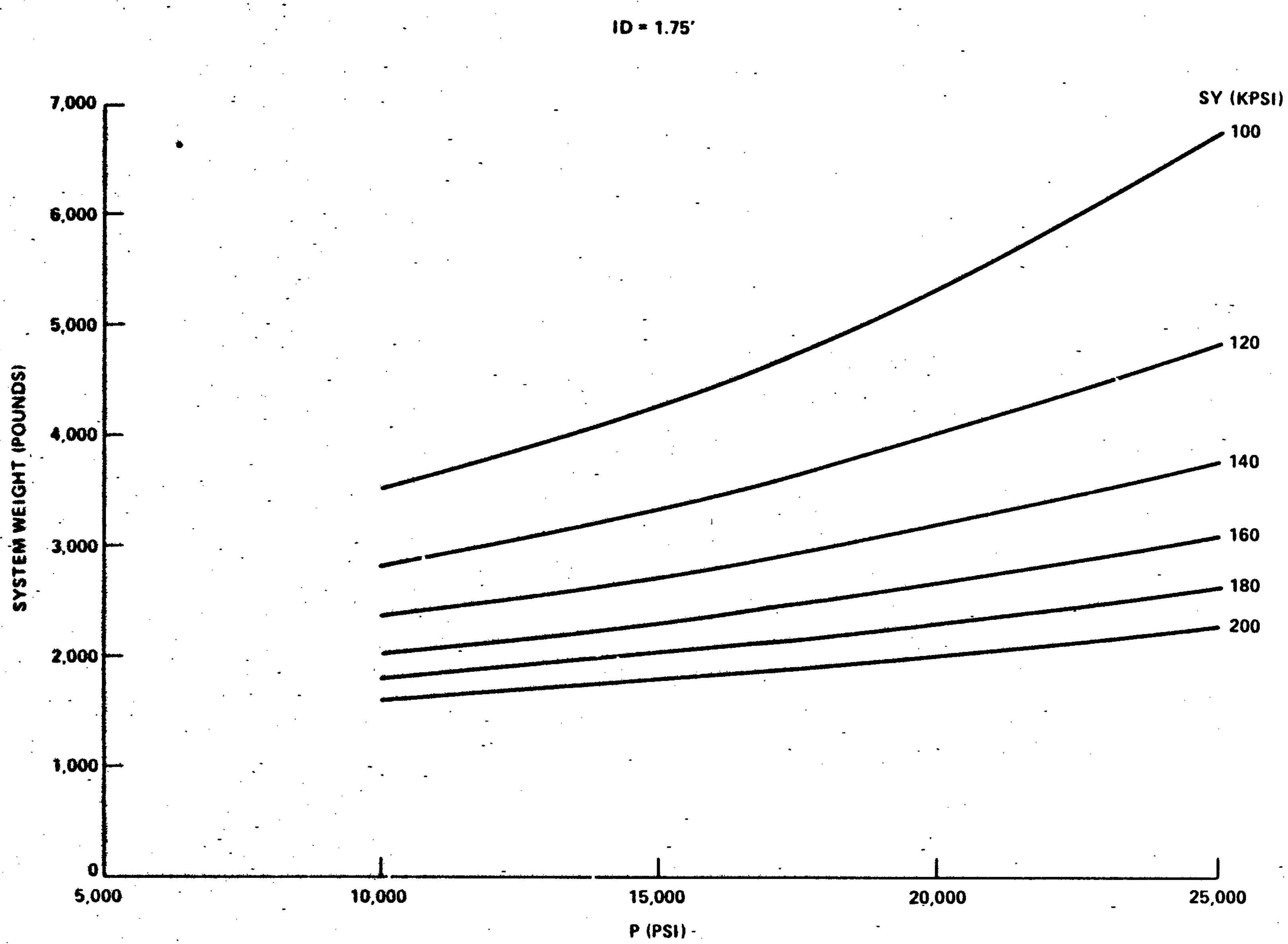


FIGURE 16. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 1.75 FEET

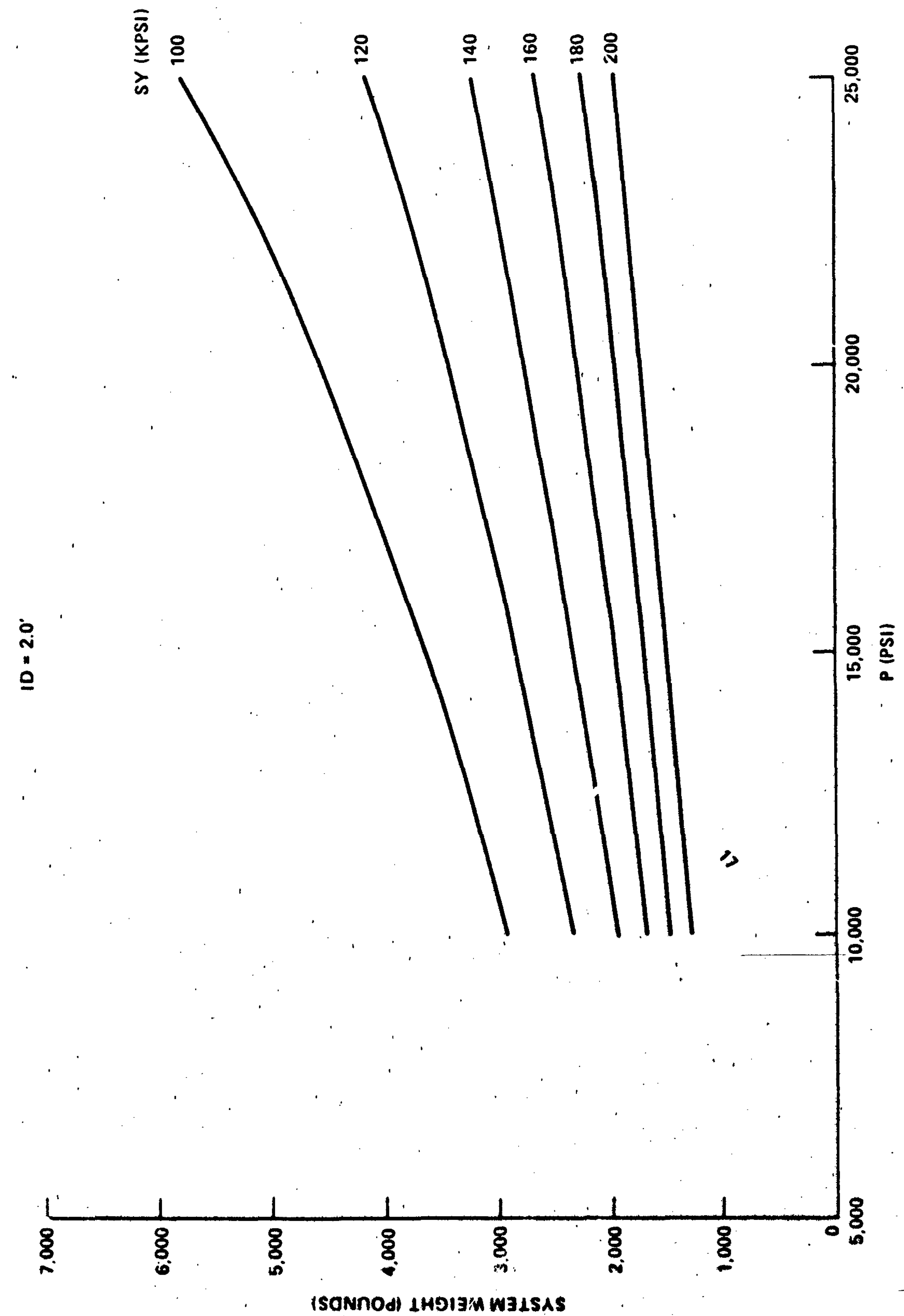


FIGURE 17. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 2.0 FEET

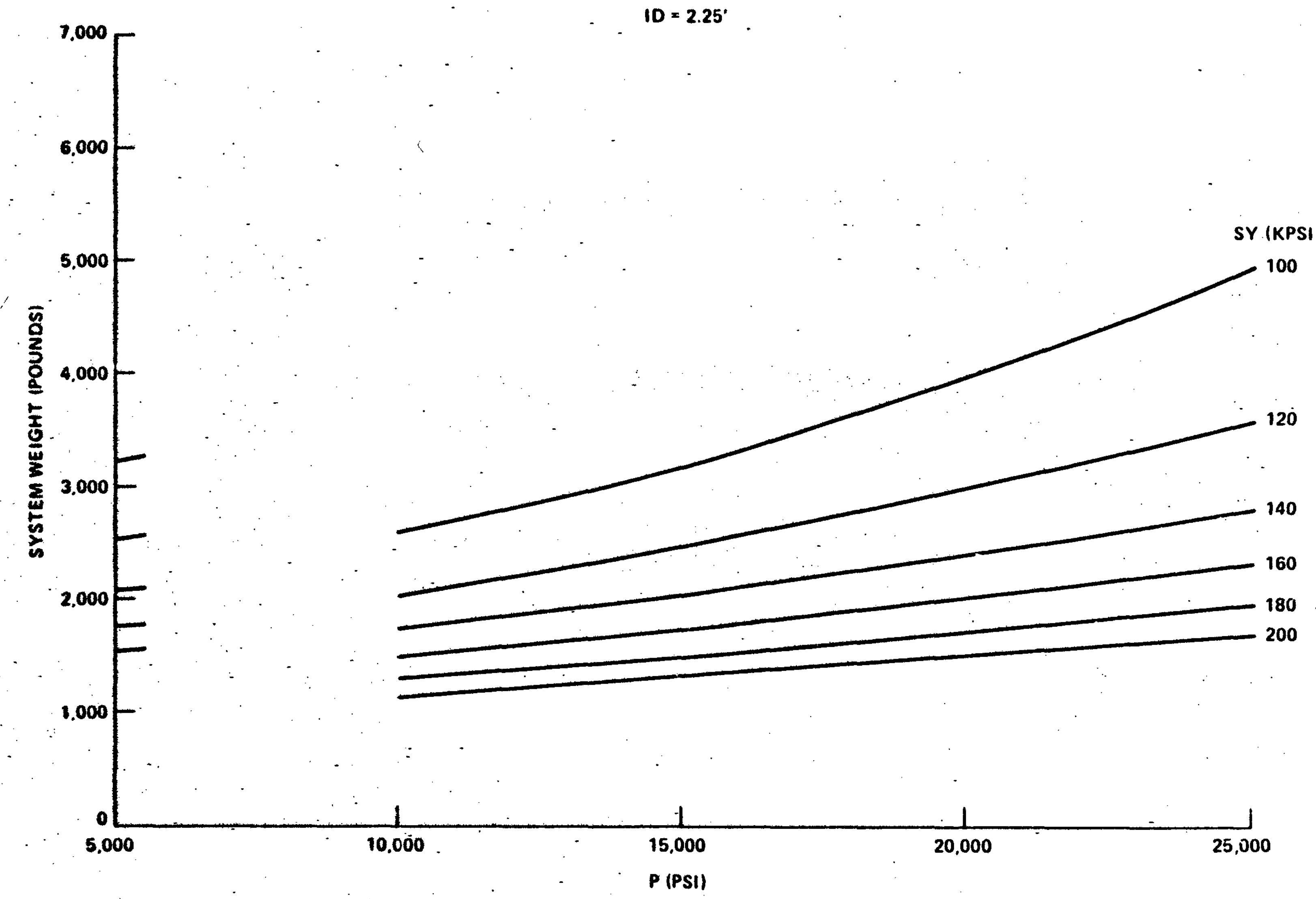


FIGURE 18. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 2.25 FEET

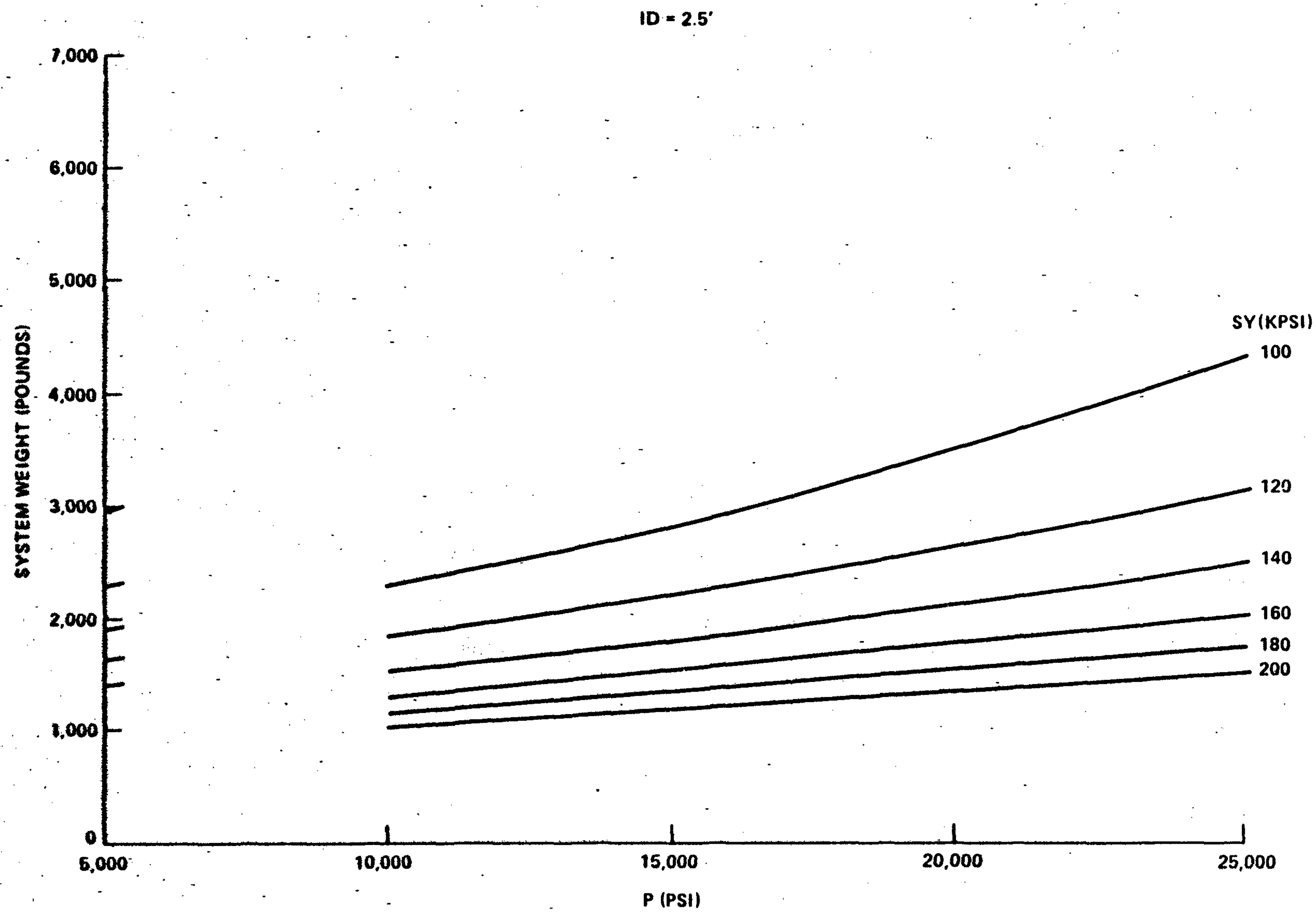


FIGURE 19. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 2.5 FEET

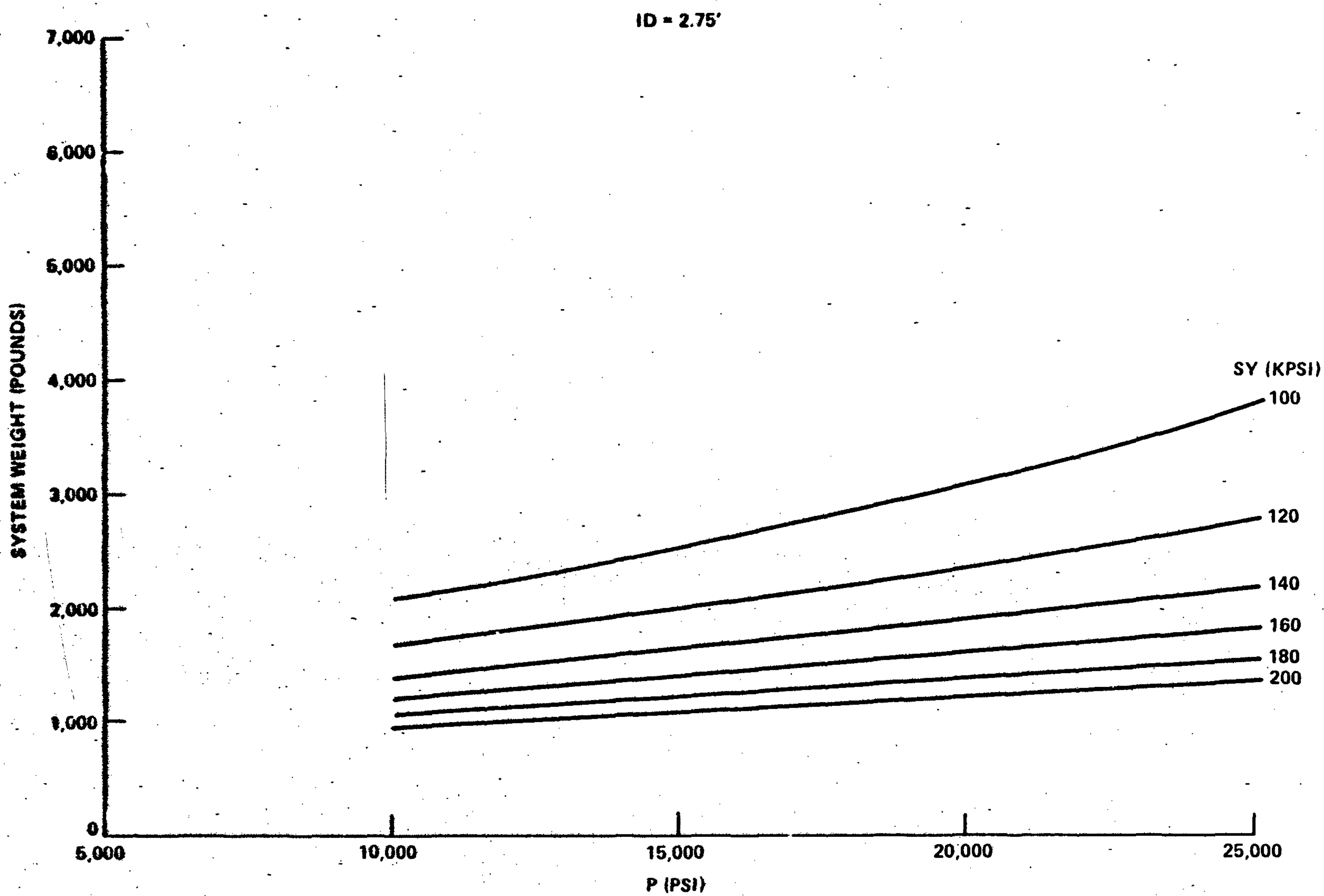


FIGURE 20. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 2.75 FEET

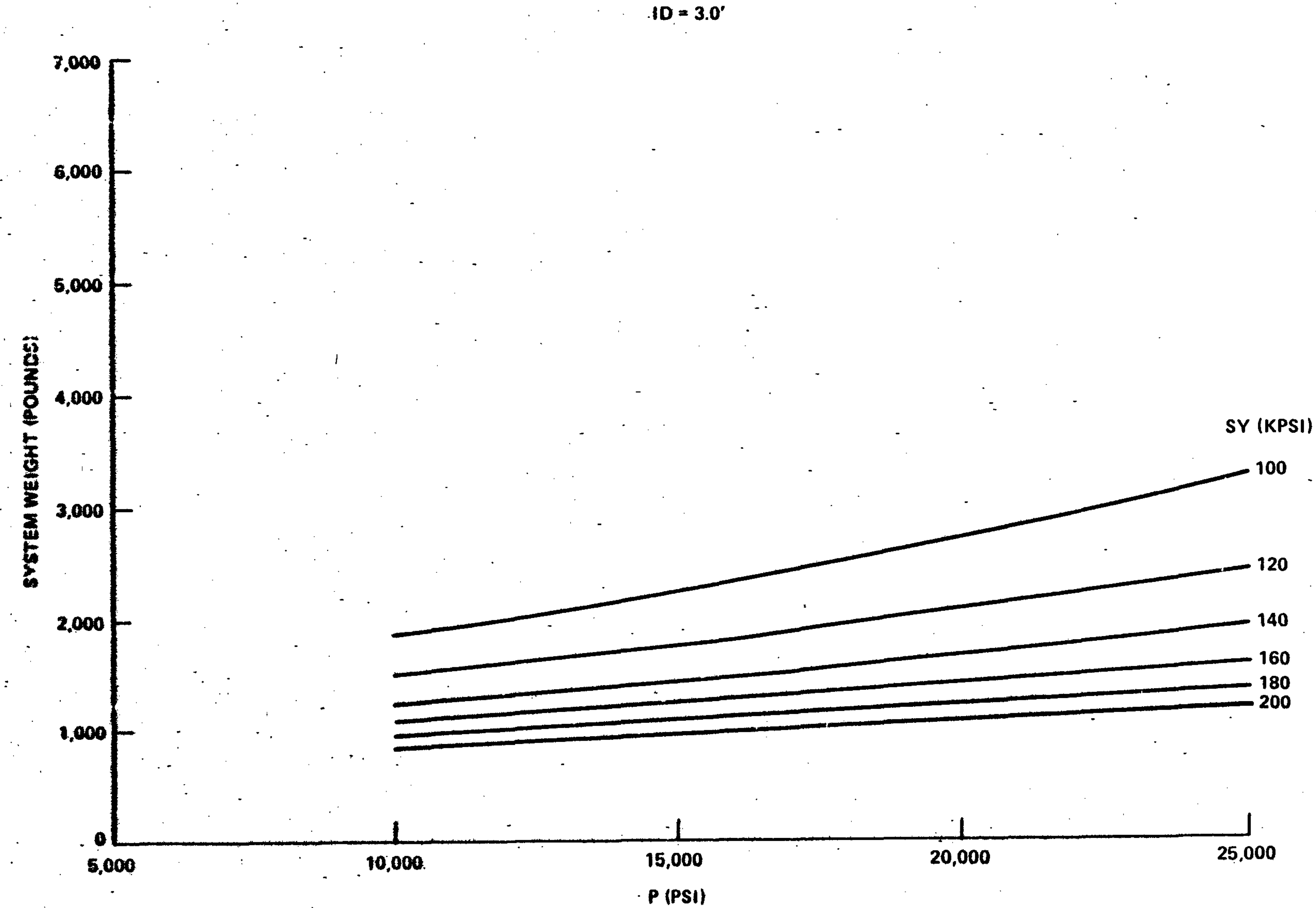


FIGURE 21. PLOT OF WATER JET SYSTEM WEIGHT VS PRESSURE AND YIELD STRESS, SY. THIS FAMILY OF CURVES IS BASED ON A WATER TUBE INSIDE DIAMETER OF 3.0 FEET

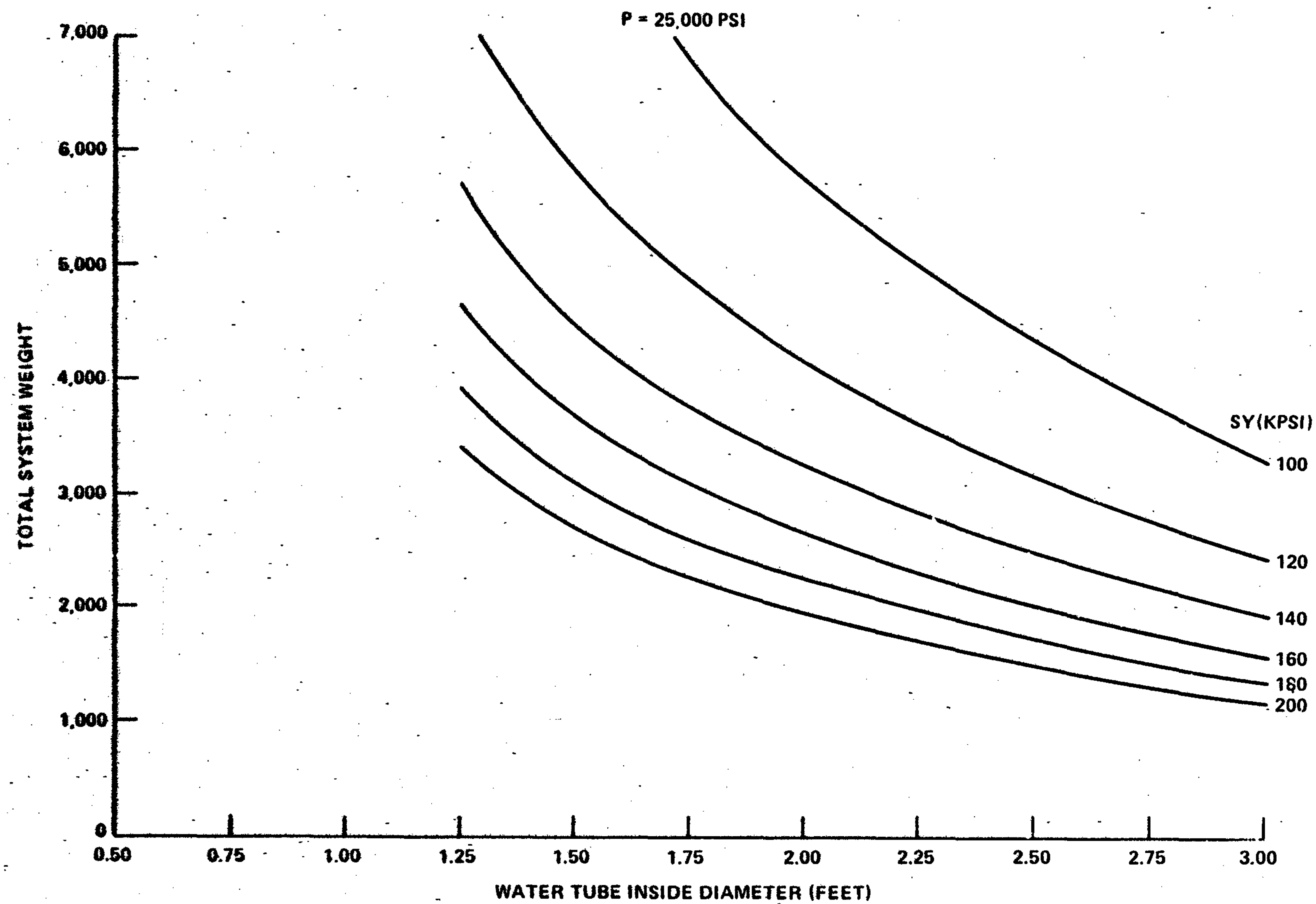


FIGURE 22. PLOT OF TOTAL WATER JET PEA WEIGHT VS WATER TUBE INSIDE DIAMETER AND YIELD STRESS. THIS FAMILY OF CURVES IS BASED ON AN OPERATING PRESSURE OF 25,000 PSI

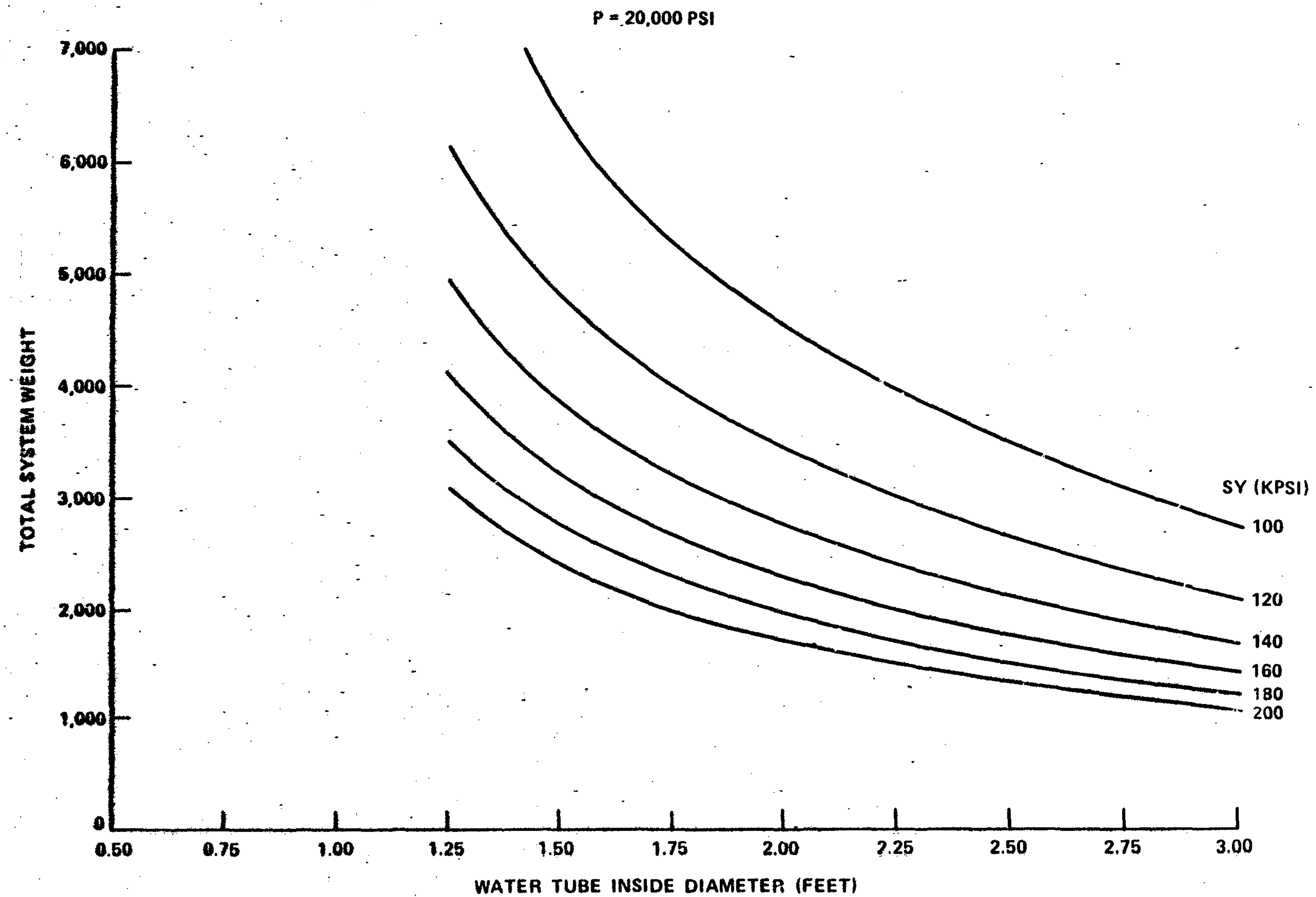


FIGURE 23. PLOT OF TOTAL WATER JET PEA WEIGHT VS WATER TUBE INSIDE DIAMETER AND YIELD STRESS. THIS FAMILY OF CURVES IS BASED ON AN OPERATING PRESSURE OF 20,000 PSI

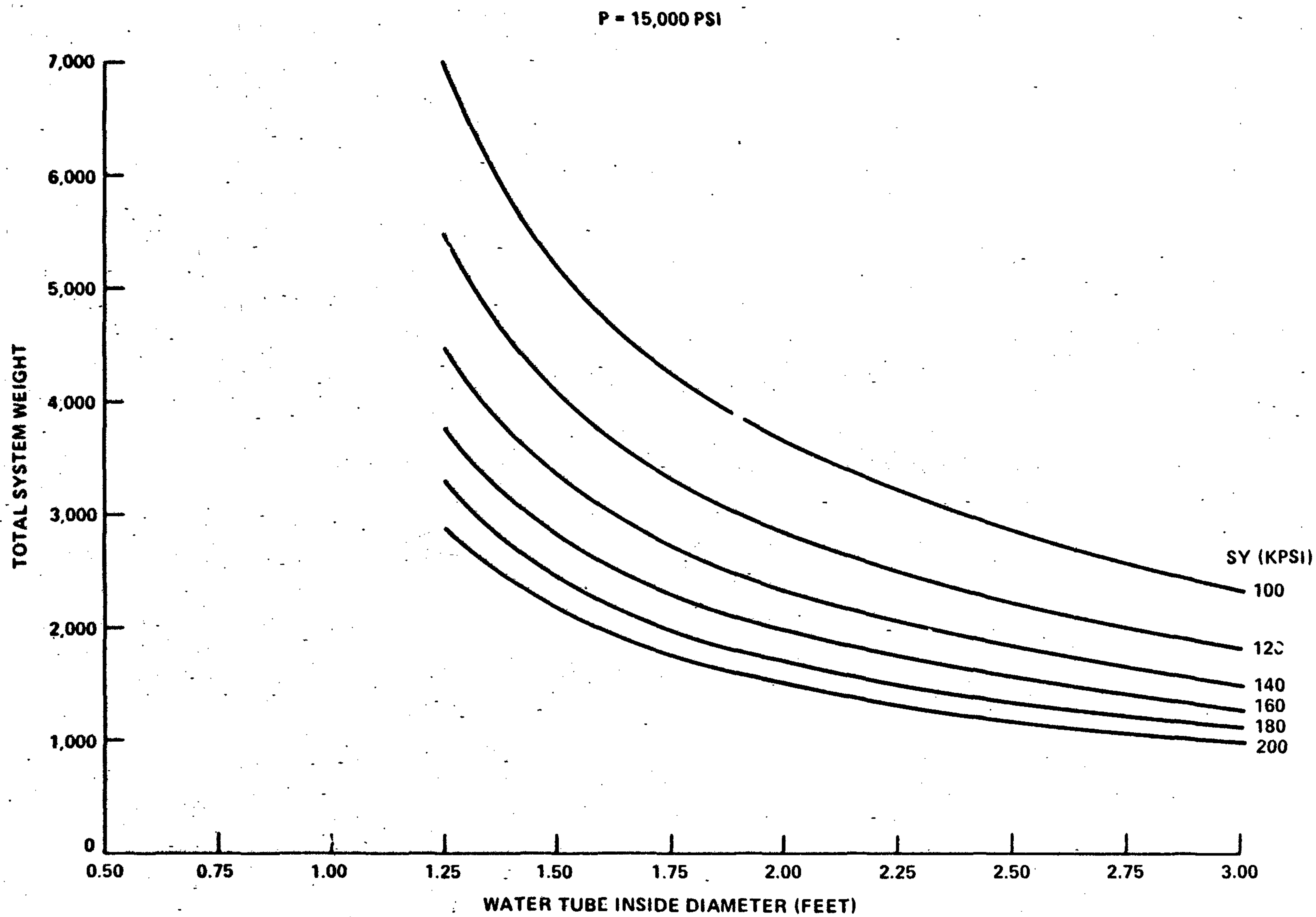


FIGURE 24. PLOT OF TOTAL WATER JET PEA WEIGHT VS WATER TUBE INSIDE DIAMETER AND YIELD STRESS. THIS FAMILY OF CURVES IS BASED ON AN OPERATING PRESSURE OF 15,000 PSI

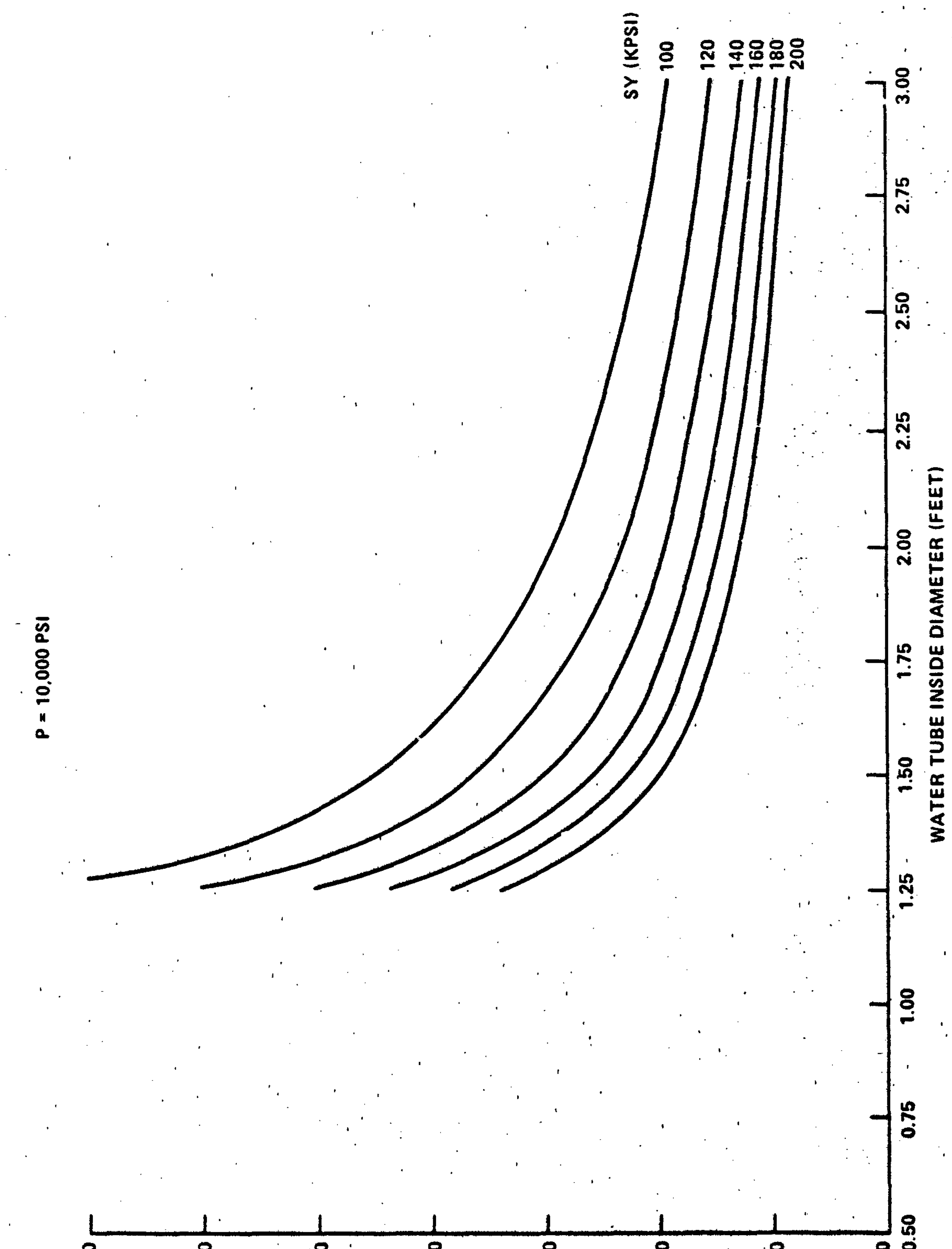


FIGURE 25. PLOT OF TOTAL WATER JET PEA WEIGHT VS WATER TUBE INSIDE DIAMETER AND YIELD STRESS. THIS FAMILY OF CURVES IS BASED ON AN OPERATING PRESSURE OF 10,000 PSI

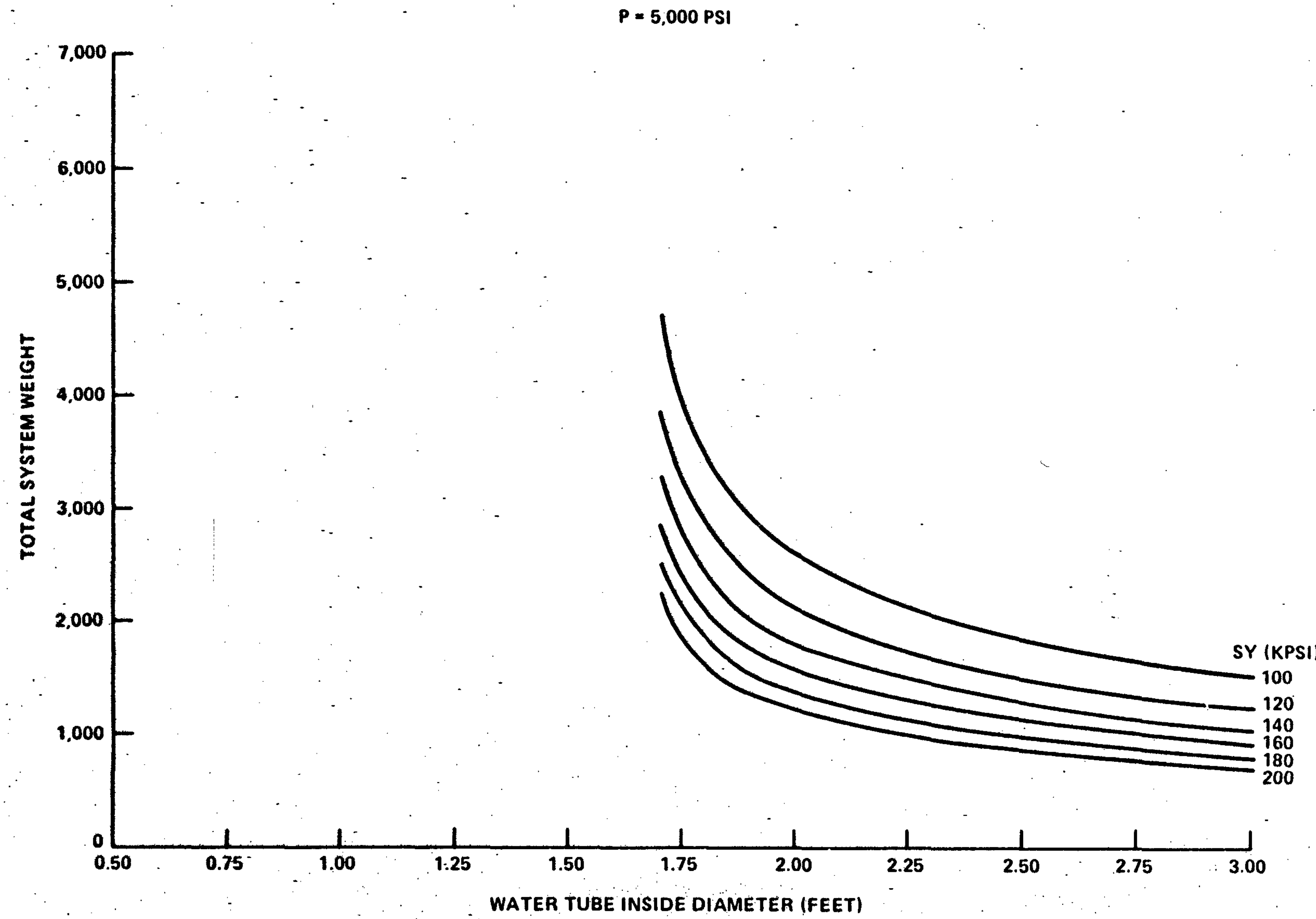


FIGURE 26. PLOT OF TOTAL WATER JET PEA WEIGHT VS WATER TUBE INSIDE DIAMETER AND YIELD STRESS. THIS FAMILY OF CURVES IS BASED ON AN OPERATING PRESSURE OF 5,000 PSI

APPENDIX A
RECOILLESS COMPUTER PROGRAM, INCLUDING ITS DESCRIPTION AND SAMPLE CALCULATIONS

The computer program included in this appendix simulates the performance of a recoilless propellant emplaced anchor. The program numerically integrates Equations B-II-5 through 14. Equation A-I-5 expresses the termination conditions, and Equation B-II-3 is used to calculate the propellant burning surface. The ideal gas equation was used to calculate the pressure instead of the modifed van der Waals equation (B-II-1), because the value for the covolume, b, was not known.

The main program, named TETHER, sets values for the constants, and reads in a file (TAPE8) of operating parameters. Any of these parameters can be changed at running time by using NAMELIST STUFF. After the input parameters have been established, the main program calculates auxiliary parameters and boundary conditions. All of the input and most of the calculated parameters are printed so that the user will have the the input parameters and the results in one output. The main program then prints the column headings and transfers control to the integration subroutine. With the aid of several other subroutines, it integrates the equations from the starting conditions to the termination condition and prints the results. Control is then returned to the main program, and the operator is queried to continue or stop. If the operator elects to continue, then he is requested to input any changed data via the NAMELIST STUFF statement. The entire process is then repeated with the new set of input data.

The integration subroutine, named RUINT, can integrate any number of simultaneous first order differential equations. It applies the Runge-Kutta method for numerical integration. From the main program, it gets several parameters such as the integration step value for the independent variable, the print frequency, the initial values, and the termination conditions. For each integration step, this subroutine must transfer to the DERIV subroutine to get current values for the derivatives. When the new values have been calculated, the time is incremented by the time step, and the new variable values are stored as old values. This process is continued until termination condition is met. Not every step is printed. The first and last steps are

printed, and every NPRINT steps, a step is printed. NPRINT was given a value of ten in this program. The individual integration steps are printed by a short subroutine named PRINT.

It is the subroutine, DERIV, which evaluates the equations listed in the first pararaph of this appendix. These are the derivatives which are integrated in RUINT. The pressure is also evaluated in DERIV by use of the equation of state. The propellant burning equations require instantaneous values of the total area of the burning surface of all the propellant grains. This calculation is done by the subroutine, SURF. The version of SURF listed in this appendix calculates the burning surface of a number, N, of seven perf propellant grains. The number and the dimensions of the grains are transferred to the function subprogram through COMMON statements. The instantaneous values of the burned distances are transferred via the argument list to SURF. The derivation of the equations is given partly in Equations B-II-3. This gives the surface of the grains until the first burnout, when the seven perfs have grown enough to become tangent. Subprogram SURF has the equations required to calculate the grains to complete burnout. While these equations aren't very complicated, their derivations are complicated. Therefore, the derivations have not been included.

A sample data set and a computer run are included along with the listing of the program. These show the way the data must be arranged and the way that the results are organized.

```
      PROGRAM TETHER(INPUT,OUTPUT,TAPE8)
      REAL MW,N,OD,ID,L,MA,MAV,ML,MLV,JAY,STROKE
      LOGICAL BEDONE
      DIMENSION Y(30),NTERM(5),TERM(5)
      COMMON /STUFF/RHOP,BEE,EN,TF,GAM,MW,N,OD,ID,L,PA,MA,FRIC,MAV,
     +ML,MLV,ACS,APIS,CDD,AT,EPS,PRN,R,CD,CFVAC,STROKE
      EXTERNAL DERIV
      DATA GEE,JAY,R/32.174,778.,49709./
      NAMELIST /STUFF/N,OD,ID,L,PINIT,VO,RHOP,BEE,EN,TF,GAM,MW,D,MA,
     +FRIC,MAV,ML,MLV,ACS,APIS,CDD,AT,EPS,STROKE
      READ(8,100)N,OD,ID,L,PINIT,VO,RHOP,BEE,EN,TF,GAM,MW,D,MA,FRIC,
     +MAV,ML,MLV,ACS,APIS,CDD,AT,EPS,STROKE
  100 FORMAT(5F16.8)
  150 READ STUFF
      PA=D*63.98+2116.8
      G1=(GAM-1.)/GAM
      GFUNC=GAM/2.+.5
      GFUNC=GFUNC**(-GFUNC/(GAM-1.))
      PRN=.2
  200 PRNOLD=PRN
      PF=SQRT(2./(GAM-1.)*(1.-PRN**G1))
      PRN=(GFUNC/EPS/PF)**GAM
      IF(ABS((PRN-PRNOLD)/PRN).GT.1.E-6) GO TO 200
      CFVAC=EPS*(2./G1*PRN**(1./GAM)-PRN*(GAM+1.)/(GAM-1.))
      AC=SQRT(GAM*R*TF/MW)
      CD=GAM*GFUNC/AC
      PRINT 300,TF,GAM,MW,PRN,CFVAC,AC,CD*GEE,RHOP*.01862,EN,
     +BEE*12*144.**EN,N,OD*12.,ID*12.,L*12.,D,MA,MAV,ACS,
     +STROKE,VO,AT,APIS,CDD,ML,MLV,EPS,FRIC
      PRINT 350
  300 FORMAT(///'PROPELLANT THERMODYNAMIC DATA'/5X'FLAME TEMP ='
     +F8.2' DEG R'/5X'SPECIFIC HEAT RATIO ='F6.4/5X'MOLECULAR WEIGHT ='
     +F6.2/5X'EXIT TO CHAMBER PRESSURE RATIO ='F6.5/5X
     +'VACUUM THRUST COEFFICIENT ='F6.4/5X'SOUND SPEED ='F10.2' FT/S'
     +/5X'DISCHARGE COEFFICIENT ='F8.6' LBM/S-LBF'
     +/5X'PROPELLANT DENSITY ='F8.5
     +' LBM/CU IN'/5X'BURNING RATE EXPONENT ='F6.5/5X
     +'BURNING RATE COEFFICIENT ='F10.8' IN/S-PSIA'///'GEOMETRIC '
     +'PROPELLANT DATA'/5X'NUMBER OF GRAINS ='F8.0/5X'OD ='F6.4' IN'
     +/5X'ID ='F6.4' IN'/5X'LENGTH ='F8.5' IN'//
     +'ANCHOR AND LAUNCHER DATA'/5X'DEPTH ='F5.0' FT'/5X
     +'ANCHOR MASS ='F6.2' SLUGS'/5X'ANCHOR VIRTUAL MASS ='F6.2' SLUGS'
     +/5X'ANCHOR CROSS SECTIONAL AREA ='F8.4' SQ FT'
     +/5X'LAUNCHER STROKE ='F8.4' FT'/5X'INITIAL FREE VOLUME ='F6.4' FT'
     +/5X'ROCKET THROAT AREA ='F8.5' SQ FT'/5X'DRIVE PISTON AREA ='
     +F8.4' SQ FT'/5X'ANCHOR DRAG COEFFICIENT ='F8.6/5X
     +'LAUNCHER MASS ='F6.2' SLUGS'/5X'LAUNCHER VIRTUAL MASS ='
     +F6.2' SLUGS'/5X'NOZZLE AREA RATIO ='F8.4/5X
     +'FRICTION FORCE ='F10.2' LBF'///)
```

```
350 FORMAT(30X'<-----VELOCITY----->
   +'<---DISPLACEMENT--->'/6X'TIME  WEB BURN  GAS MASS
   +'ANCHOR  LAUNCHER   ANCHOR  LAUNCHER   GAS VOL  GAS TEMP  PRES'
   +'SURE    THRUST'/5X'(SEC)'6X'(IN)    (SLUG)    (FT/S)    (FT/S)'
   +6X'(FT)'6X'(FT)   (CU FT)   (DEG R)    (PSIA)  (POUNDS)'///)
    DO 400 I=1.10
400 Y(I)=0.
    Y(3)=PINIT*VO*MW/R/TF
    Y(8)=VO
    Y(9)=TF
    Y(15)=PINIT
    Y(16)=PINIT*AT*CFVAC-EPS*AT*PA
    NTERM(1)=10
    TERM(1)=STROKE
    CALL RUINT(10..0001.10..T..Y.1.NTERM.TERM.DERIV)
    READ*.BEDONE
    IF(.N.BEDONE) GO TO 150
    STOP
    END



    SUBROUTINE RUINT(NUM.H.NPRINT.INIT.YNEW.NTC.NTERM.TERM.DERIV)
    DIMENSION YNEW(30).YOLD(30).D(30).B(4).Q(4.30).NTERM(30).
   + TERM(30)
    INTEGER COUNT
    LOGICAL INIT
    EQUIVALENCE(YOLD(1).TOLD)
    DATA B(1).B(2)/.5..5/.B(3).B(4)/1..1./.COUNT.N/0.0/.D(1)/1./
    HH=-HH
    HSAVE=0.
    N=COUNT+MOD(N-COUNT.NPRINT)
    MTC=1
    IF(.NOT.INIT) GO TO 100
    CALL PRINT(NUM.YNEW)
    COUNT=0
    N=NPRINT
50   HH=H
100  DO 150 J=1.NUM
150  YOLD(J)=YNEW(J)
    DO 250 J=1.4
    CALL DERIV(NUM.YNEW.D.HH*B(J))
    DO 200 I=1.NUM
    Q(J.I)=D(I)*HH
200  YNEW(I)=YOLD(I)+Q(J.I)*B(J)
250  CONTINUE
    DO 300 I=1.NUM
300  YNEW(I)=YOLD(I)+(Q(1.I)+Q(4.I))/6.+(Q(2.I)+Q(3.I))/3.
    IF(MTC.GT.NTC) GO TO 380
    DO 375 J=MTC.NTC
    LTC=IABS(NTERM(J))
    IF(YNEW(LTC)*NTERM(J).LT.TERM(J)*NTERM(J)) GO TO 375
    MTC=J+1
```

```
      HH=(TERM(J)-YNEW(LTC))/D(LTC)
      HSAVE=HSAVE+HH
      GO TO 100
375    CONTINUE
380    CONTINUE
      IF(HH.GT.0.) GO TO 400
      CALL PRINT (NUM,YNEW)
      HH=HSAVE
      RETURN
400    COUNT=COUNT+1
      IF (COUNT.NE.N)GO TO 50
      CALL PRINT (NUM, YNEW)
      N=N+NPRINT
      GO TO 50
      END



      SUBROUTINE DERIV(NUM,Y,D,DELT)
      REAL MW,MA,MAV,ML,MLV,JAY
      DIMENSION Y(30),D(30)
      COMMON /STUFF/RHOP,BEE,EN,TF,GAM,MW,N,OD,ID,L,PA,MA,FRIC,MAV,
     +ML,MLV,ACS,APIS,CDD,AT,EPS,PRN,R,CD,CFVAC,STROKE
      JAY=778.
      Y(15)=Y(3)*R*Y(9)/MW/Y(8)
      Y(16)=Y(15)*AT*(CFVAC-EPS*PA/Y(15))
      D(2)=BEE*Y(15)**EN
      GPR=RHOP*SURF(Y(2))*D(2)
      IF(GPR.EQ.0.)D(2)=0.
      GEX=Y(15)*AT*CD*SQRT(TF/Y(9))
      D(3)=GPR-GEX
      D(4)=(APIS*(Y(15)-PA)-FRIC-.7944*ACS*Y(4)**2*CDD)/(MA+MAV)
      D(5)=(APIS*(Y(15)-PA)-FRIC-Y(15)*AT*(CFVAC-EPS*PA/Y(15)))/(ML+MLV)
      D(6)=Y(4)
      D(7)=Y(5)
      D(10)=Y(4)+Y(5)
      D(8)=APIS*(Y(4)+Y(5))+GPR/RHOP
      D(9)=(Y(3)*Y(7)+GPR*DELT*TF)/(Y(3)+GPR*DELT)-(GAM-1.)*Y(9)/
     +Y(8)*(D(8)-GPR/RHOP)
      RETURN
      END



      SUBROUTINE PRINT(N,Y)
      DIMENSION Y(30)
      PRINT 100,Y(1),Y(2)*12.,Y(3),Y(4),Y(5),Y(6),Y(7),Y(8),Y(9),
     +Y(15)/144.,Y(16)
100   FORMAT(3F10.6,5F10.4,2F10.2,F10.0)
      RETURN
      END
```

```
      FUNCTION SURF(X)
      REAL N,L,ID,OD,LO
      COMMON /STUFF/RHOP,BEE,EN,TF,GAM,MW,N,OD,ID,LO,PA,MA,FRIC,MAV,
     +ML,MLV,ACS,APIS,CDD,AT,EPS,PRN,R,CD,CFVAC,STROKE
      PI=3.1415926536
      RIO=ID/2.
      ROO=OD/2.
      RI=RIO+X
      RO=ROO-X
      L=LO-2.*X
      S=(RI+RO)/2.
      SURF=0.
      IF(L.LE.0..OR.RO/RI.LE.3./(5.-2.*SQRT(3.))) RETURN
      SURF=2.*PI*(L*(RO+7.*RI)+RO**2-7.*RI**2)*N
      IF(RI.LT.S/2.) RETURN
      BETA=ASIN((5.*RO-3.*RI)/4./RO)
      GAMMA=BETA-PI/3.
      EPSILON=ACOS((RO+RI)/4./RI)
      IOTA=ASIN(RO/RI*COS(BETA))
      ALPHA=2.*PI/3.-EPSILON-IOTA
      SIGMA=PI/3.-2.*EPSILON
      SURF=6.*(2*L*(RO*GAMMA+RI*ALPHA)+RO*SIN(GAMMA)*SQRT((2.*RI*SIN(
     +ALPHA/2.))**2-(RO*SIN(GAMMA))**2)-RI**2*(ALPHA-SIN(ALPHA))
     ++.5*RO**2*(2.*GAMMA-SIN(2.*GAMMA)))*N
      IF(RI.GT.S/SQRT(3.)) RETURN
      SURF=SURF+(1.5*SQRT(3.)*S**2-9.*S*SQRT(RI**2-(S/2.)**2)
     +-9.*RI**2*SIGMA+18.*RI*L*SIGMA)*N
      RETURN
      END
```

```
TAPE8

   150.          .31666667     .01666667     .5        864000.
     1.         3.28           .0000044      .81         5750.
     1.22      28.12        300.          200.           1000.
    50.       700.           50.            3.              .6
      .1         .5           5.5           6.
EOI ENCOUNTERED.
```

```
? $STUFF $

PROPELLANT THERMODYNAMIC DATA
     FLAME TEMP = 5750.00 DEG R
     SPECIFIC HEAT RATIO =1.2200
     MOLECULAR WEIGHT = 28.12
     EXIT TO CHAMBER PRESSURE RATIO =.02678
     VACUUM THRUST COEFFICIENT =1.6516
     SOUND SPEED =   3521.47 FT/S
     DISCHARGE COEFFICIENT = .006584 LBM/S-LBF
     PROPELLANT DENSITY =  .06107 LBM/CU IN
     BURNING RATE EXPONENT =.81000
     BURNING RATE COEFFICIENT = .00290738 IN/S-PSIA

GEOMETRIC PROPELLANT DATA
     NUMBER OF GRAINS =    150.
     OD =3.8000 IN
     ID = .2000 IN
     LENGTH = 6.00000 IN

ANCHOR AND LAUNCHER DATA
     DEPTH = 300. FT
     ANCHOR MASS =200.00 SLUGS
     ANCHOR VIRTUAL MASS = 50.00 SLUGS
     ANCHOR CROSS SECTIONAL AREA =  3.0000 SQ FT
     LAUNCHER STROKE =  6.0000 FT
     INITIAL FREE VOLUME =1.0000 FT
     ROCKET THROAT AREA =  .50000 SQ FT
     DRIVE PISTON AREA =   .6000 SQ FT
     ANCHOR DRAG COEFFICIENT = .100000
     LAUNCHER MASS =700.00 SLUGS
     LAUNCHER VIRTUAL MASS = 50.00 SLUGS
     NOZZLE AREA RATIO =  5.5000
     FRICTION FORCE =   1000.00 LBF
```

TIME (SEC)	WEB BURN (IN)	GAS MASS (SLUG)	VELOCITY ANCHOR (FT/S)	VELOCITY LAUNCHER (FT/S)	DISPLACEMENT ANCHOR (FT)	DISPLACEMENT LAUNCHER (FT)	GAS VOL (CU FT)	GAS TEMP (DEG R)	PRESSURE (PSIA)	THRUST (POUNDS)
0.000000	0.000000	.035001	0.0000	0.0000	0.0000	0.0000	1.0000	5750.00	6000.00	654898.
.001000	.003792	.113920	2.3208	-.2383	.0011	-.0001	1.0403	5755.01	7736.64	861413.
.002000	.008322	.144247	5.2234	-.5796	.0048	-.0005	1.0900	5758.39	9255.28	1053978.
.003000	.013500	.175509	8.6572	-.9276	.0117	-.0012	1.1485	5759.97	10805.56	1226361.
.004000	.019237	.207566	12.5609	-1.3645	.0223	-.0024	1.2153	5759.67	12075.71	1377403.
.005000	.025450	.240476	16.8737	-1.8527	.0370	-.0040	1.2900	5757.49	13176.16	1506265.
.006000	.032067	.274399	21.5401	-2.3853	.0562	-.0061	1.3719	5753.51	14127.26	1621368.
.007000	.039030	.309530	26.5124	-2.9564	.0802	-.0089	1.4607	5747.83	14951.78	1719410.
.008000	.046290	.346068	31.7507	-3.5600	.1093	-.0120	1.5562	5740.59	15671.73	[illegible]
.009000	.053809	.384197	37.2216	-4.1945	.1438	-.0159	1.6581	5731.91	16323.83	1880197.
.010000	.061553	.424081	42.8980	-4.8540	.1838	-.0204	1.7663	5721.96	16885.18	1946953.
.011000	.069497	.465862	48.7573	-5.5365	.2296	-.0256	1.8805	5710.87	17367.55	2006694.
.012000	.077620	.509661	54.7808	-6.2397	.2814	-.0315	2.0008	5698.78	17820.80	2060593.
.013000	.085905	.555583	60.9528	-6.9617	.3392	-.0381	2.1269	5685.81	18232.70	2109575.
.014000	.094335	.603714	67.2600	-7.7007	.4033	-.0454	2.2589	5672.09	18609.43	2154375.
.015000	.102900	.654129	73.6911	-8.4554	.4738	-.0535	2.3967	5657.71	18955.88	2195573.
.016000	.111587	.706887	80.2360	-9.2245	.5507	-.0623	2.5403	5642.78	19275.92	2233632.
.017000	.120387	.762040	86.8862	-10.0070	.6343	-.0720	2.6896	5627.39	19572.69	2268922.
.018000	.129292	.819628	93.6339	-10.8019	.7245	-.0824	2.8447	5611.61	19840.68	2301743.
.019000	.138295	.879685	100.4722	-11.6083	.8216	-.0936	3.0054	5595.51	20105.96	2332338.
.020000	.147388	.942235	107.3948	-12.4256	.9255	-.1056	3.1718	5579.15	20346.20	2360937.
.021000	.156566	1.007275	114.3958	-13.2529	1.0364	-.1184	3.3438	5562.57	20570.80	2387611.
.022000	.165823	1.074878	121.4701	-14.0896	1.1543	-.1321	3.5215	5545.80	20780.72	2412602.
.023000	.175153	1.144989	128.6125	-14.9351	1.2794	-.1466	3.7047	5529.06	20977.53	2435984.
.024000	.184552	1.217627	135.8185	-15.7889	1.4116	-.1620	3.8936	5512.17	21161.53	2457863.
.025000	.194015	1.292789	143.0836	-16.6504	1.5510	-.1782	4.0880	5495.25	21333.59	2478324.
.026000	.203539	1.370462	150.4037	-17.5191	1.6978	-.1953	4.2879	5478.31	21494.37	2497443.
.027000	.213118	1.450633	157.7749	-18.3946	1.8518	-.2132	4.4934	5461.40	21644.42	2515237.
.028000	.222749	1.533282	165.1934	-19.2763	2.0133	-.2321	4.7043	5444.53	21784.25	2531915.
.029000	.232429	1.618386	172.6556	-20.1639	2.1822	-.2513	4.9207	5427.72	21914.30	2547300.
.030000	.242154	1.705917	180.1580	-21.0569	2.3587	-.2724	5.1426	5411.00	22034.98	2561731.

.031000	.251920	1.795845	187.6974	-21.9549	2.5426	-.2939	5.3698	5394.37	22146.65	2575010.
.032000	.261725	1.888134	195.2704	-22.8576	2.7341	-.3163	5.6024	5377.85	22249.66	2587260.
.033000	.271565	1.982747	202.8740	-23.7646	2.9331	-.3396	5.8404	5361.45	22344.32	2598517.
.034000	.281437	2.079643	210.5053	-24.6755	3.1398	-.3638	6.0836	5345.18	22430.93	2608816.
.035000	.291339	2.178727	218.1613	-25.5900	3.3541	-.3890	6.3321	5329.05	22509.76	2618191.
.036000	.301268	2.280102	225.8392	-26.5078	3.5761	-.4150	6.5859	5313.07	22581.09	2626672.
.037000	.311221	2.383569	233.5364	-27.4284	3.8058	-.4420	6.[illegible]448	5297.24	22645.14	2634290.
.038000	.321195	2.489125	241.2502	-28.3518	4.0432	-.4699	7.1088	5281.57	22702.17	2641071.
.039000	.331189	2.596717	248.9781	-29.2774	4.2883	-.4987	7.3780	5266.06	22752.39	2647043.
.040000	.341199	2.706288	256.7176	-30.2051	4.5412	-.5284	7.6523	5250.71	22796.02	2652232.
.041000	.351224	2.817779	264.4664	-31.1345	4.8018	-.5591	7.9315	5235.54	22833.27	2656661.
.042000	.361260	2.931130	272.2220	-32.0654	5.0701	-.5907	8.2158	5220.54	22864.34	2660356.
.043000	.371307	3.046280	279.9823	-32.9975	5.3462	-.6232	8.5050	5205.71	22889.42	2663339.
.044000	.381362	3.163164	287.7451	-33.9306	5.6301	-.6567	8.7990	5191.05	22908.70	2665631.
.045000	.391422	3.281717	295.5082	-34.8644	5.9217	-.6911	9.0979	5176.57	22922.36	2667256.
.046000	.401486	3.397809	303.2692	-35.7986	6.2211	-.7264	9.4003	5162.26	22905.98	2665307.
.047000	.411468	3.435736	310.9451	-36.7228	6.5282	-.7627	9.6821	5148.11	22426.22	2608257.
.047846	.419748	3.431072	317.2743	-37.4846	6.7941	-.7941	9.9103	5136.22	21829.43	2537288.

APPENDIX B

DIRECT ROCKET COMPUTER PROGRAM, INCLUDING ITS DESCRIPTION AND A SAMPLE CALCULATION

While the mechanism of the direct rocket PEA is significantly different from that of the recoilless PEA, their performances can be simulated by very similar computer programs. The recoilless PEA has two parts which move differently, although interdependently. The anchor moves forward under the force of the gas pressure acting on a piston, less the internal and external frictions. The recoilless launcher is accelerated backward by the same force, a pressure on a piston. This force is diminished by the same small internal friction that affects the anchor and by the very large rocket thrust. The net force acting on the launcher should be vey small as compared to the force acting on the anchor. Since the net force acting on the launcher is a small difference between two large forces, that small net force could be positive or negative. A positive force would cause the launcher to accelerate to the rear; a negative force would accelerate it forward. Regardless of the sign of the force, its magnitude will be reduced by the external friction. The effective masses of the anchor and the launcher are both increased by their virtual masses. The mass of the launcher is steadily decreasing because of the propellant gases being ejected. The temperature of the gases inside the combustion chamber and piston must be computed continuously because the gas is doing expansion work and new propellant gas is continuously being mixed with the older gas.

The direct rocket moves as a single unit; therefore, only one velocity and displacement must be integrated. There is no internal drag. The force accelerating the whole system is equal to the rocket thrust less the external hydrodynamic force. The net mass is increased by the virtual mass and decreased by mass of the propellant gas exhausted. The propellant temperature remains constant inside the combustion chamber, because the gas does no expansion work until it reaches the nozzle.

Because the details of the calculations are so similar to those of the recoilless PEA, it was most efficient to modify the recoilless program to handle the direct rocket. The SURF subprogram was changed to handle single perf propellant grains because the direct rocket does not need a progressive burn.

```
      PROGRAM DIRROC(INPUT,OUTPUT.TAPE8)
      REAL MW.N.OD.ID.L.MA.MAV.JAY.STROKE
      LOGICAL BEDONE
      DIMENSION Y(30).NTERM(5),TERM(5)
      COMMON /STUFF/RHOP.BEE.EN.TF.GAM.MW.N.OD.ID.L.PA.MA.MAV.
     +ACS.CDD.AT.EPS.PRN.R.CD.CFVAC.STROKE
      EXTERNAL DERIV
      DATA GEE.JAY.R/32.174.778..49709./
      NAMELIST /STUFF/N.OD.ID.L.PINIT.VO.RHOP.BEE.EN.TF.GAM.MW.D.MA.
     +MAV.ACS.CDD.AT.EPS.STROKE
      READ(8,100)N.OD.ID.L.PINIT.VO.RHOP.BEE.EN.TF.GAM.MW.D.MA.
     +MAV.ACS.CDD.AT.EPS.STROKE
  100 FORMAT(5F16.8)
  150 READ STUFF
      PI=4.*ATAN(1.)
      PA=D*63.98+2116.8
      G1=(GAM-1.)/GAM
      GFUNC=GAM/2.+.5
      GFUNC=GFUNC**(-GFUNC/(GAM-1.))
      PRN=.2
  200 PRNOLD=PRN
      PF=SQRT(2./(GAM-1.)*(1.-PRN**G1))
      PRN=(GFUNC/EPS/PF)**GAM
      IF(ABS((PRN-PRNOLD)/PRN).GT.1.E-6) GO TO 200
      CFVAC=EPS*(2./G1*PRN**(1./GAM)-PRN*(GAM+1.)/(GAM-1.))
      AC=SQRT(GAM*R*TF/MW)
      CD=GAM*GFUNC/AC
      PROPM=N*RHOP*PI*L*(OD**2-ID**2)/4.
      PRINT 300.TF,GAM.MW,PRN,CFVAC.AC.CD*GEE.RHOP*.01862.EN.
     +BEE*12*144.**EN.N.OD*12.,ID*12..L*12..D,MA,MAV,PROPM.ACS.
     +STROKE.VO,AT.CDD,EPS
      PRINT 350
  300 FORMAT(//'PROPELLANT THERMODYNAMIC DATA'/5X'FLAME TEMP ='
     +F8.2' DEG R'/5X'SPECIFIC HEAT RATIO ='F6.4/5X'MOLECULAR WEIGHT ='
     +F6.2/5X'EXIT TO CHAMBER PRESSURE RATIO ='F6.5/5X
     +'VACUUM THRUST COEFFICIENT ='F6.4/5X'SOUND SPEED ='F10.2' FT/S'
     +/5X'DISCHARGE COEFFICIENT ='F8.6' LBM/S-LBF'
     +/5X'PROPELLANT DENSITY ='F8.5
     +' LBM/CU IN'/5X'BURNING RATE EXPONENT ='F6.5/5X
     +'BURNING RATE COEFFICIENT ='F10.8' IN/S-PSIA'//'GEOMETRIC '
     +'PROPELLANT DATA'/5X'NUMBER OF MONOPERF GRAINS ='F8.0
     +/5X'OD ='F6.4' IN'/5X'ID ='F6.4' IN'/5X'LENGTH ='F8.5' IN'//
     +'SYSTEM DATA'/5X'DEPTH ='F5.0' FT'/5X
     +'SYSTEM MASS ='F6.2' SLUGS'/5X'SYSTEM VIRTUAL MASS ='F6.2' SLUGS'
     +/5X'PROPELLANT MASS ='F10.4' SLUGS'
     +/5X'SYSTEM CROSS SECTIONAL AREA ='F8.4' SQ FT'
     +/5X'STROKE ='F8.4' FT'/5X'INITIAL FREE VOLUME ='F9.4' FT'
     +/5X'ROCKET THROAT AREA ='F8.5' SQ FT'
     +/5X'ANCHOR DRAG COEFFICIENT ='F8.6
     +/5X'NOZZLE AREA RATIO ='F8.4///)
```

```
350 FORMAT(6X'TIME  WEB BURN  GAS MASS PROP MASS'
   +'  VELOCITY  DISTANCE  GAS VOL  PRES'
   +'SURE    THRUST'/5X'(SEC)'6X'(IN)    (SLUG)    (SLUG)    (FT/S)'
   +6X'(FT)    (CU FT)    (PSIA)  (POUNDS)'//)
    DO 400 I=1,10
400 Y(I)=0.
    Y(3)=PINIT*VO*MW/R/TF
    Y(7)=VO
    Y(4)=PROPM
    Y(9)=TF
    Y(15)=PINIT
    Y(16)=PINIT*AT*CFVAC-EPS*AT*PA
    NTERM(1)=6
    TERM(1)=STROKE
    CALL RUINT(7,.0001,10,.T.,Y,1,NTERM,TERM,DERIV)
    PRINT 500
500 FORMAT(//'DO YOU WANT TO STOP (.T.) OR CONTINUE (.F.) COMPUTING?')
    READ*,BEDONE
    IF(.N.BEDONE) GO TO 150
    STOP
    END


    SUBROUTINE RUINT(NUM,H,NPRINT,INIT,YNEW,NTC,NTERM,TERM,DERIV)
    DIMENSION YNEW(30),YOLD(30),D(30),B(4),Q(4,30),NTERM(30),
   + TERM(30)
    INTEGER COUNT
    LOGICAL INIT
    EQUIVALENCE(YOLD(1),TOLD)
    DATA B(1),B(2)/.5,.5/,B(3),B(4)/1.,1./,COUNT,N/0,0/,D(1)/1./
    HH=-H
    HSAVE=0.
    N=COUNT+MOD(N-COUNT,NPRINT)
    NTC=1
    IF(.NOT.INIT) GO TO 100
    CALL PRINT(NUM,YNEW)
    COUNT=0
    N=NPRINT
50  [illegible]
100 DO 150 J=1,NUM
150 YOLD(J)=YNEW(J)
    DO 250 J=1,4
    CALL DERIV(NUM,YNEW,D,HH*B(J))
    DO 200 I=1,NUM
    Q(J,I)=D(I)*H
200 YNEW(I)=YOLD(I)+Q(J,I)*B(J)
250 CONTINUE
    DO 300 I=1,NUM
300 YNEW(I)=YOLD(I)+(Q(1,I)+Q(4,I))/6.+(Q(2,I)+Q(3,I))/3.
    IF(NTC.GT.NTC) GO TO 500
    DO 375 J=NTC,NTC
    LTC=IABS(NTERM(J))
    IF(YNEW(LTC)*NTERM(J).LT.TERM(J)*NTERM(J)) GO TO 375
```

```
      MTC=J+1
      HH=(TERM(J)-YNEW(LTC))/D(LTC)
      HSAVE=HSAVE+HH
      GO TO 100
375    CONTINUE
380    CONTINUE
      IF(HH.GT.0.) GO TO 400
      CALL PRINT (NUM,YNEW)
      HH=HSAVE
      RETURN
400    COUNT =COUNT+1
      IF (COUNT.NE.N)GO TO 50
      CALL PRINT (NUM, YNEW)
      N=N+NPRINT
      GO TO 50
      END
```

```
      SUBROUTINE DERIV(NUM,Y,D,DELT)
      REAL MW,MA,MAV,JAY
      DIMENSION Y(30),D(30)
      COMMON /STUFF/RHOP,BEE,EN,TF,GAM,MW,N,OD,ID,L,PA,MA,MAV,
     +ACS,CDD,AT,EPS,PRN,R,CD,CFVAC,STROKE
      JAY=778.
      Y(15)=Y(3)*R*TF/MW/Y(7)
      Y(16)=Y(15)*AT*(CFVAC-EPS*PA/Y(15))
      D(2)=BEE*Y(15)**EN
      GPR=RHOP*SURF(Y(2))*D(2)
      IF(GPR.EQ.0.)D(2)=0.
      GEX=Y(15)*AT*CD
      D(3)=GPR-GEX
      D(4)=-GEX
      DRAG=.7944*ACS*Y(5)**2*CDD
      D(5)=(Y(15)*AT*(CFVAC-EPS*PA/Y(15))-DRAG)/(MA+Y(7)*MAV)
      D(6)=Y(5)
      D(7)=GPR/RHOP
      RETURN
      END
```

```
      SUBROUTINE PRINT(J,Y)
      DIMENSION Y(30)
      PRINT 100,Y(1),Y(2)*12.,Y(3),Y(4),Y(5),Y(6),Y(7),
     *Y(15)/144.,Y(16)
100   FORMAT(3F10.6,4F10.4,F10.2,F10.0)
      RETURN
      END
```

```
      FUNCTION SURF(X)
      REAL N,L,ID,OD,LO
      COMMON /STUFF/RHOP,BEE,EN,TF,GAM,MW,N,OD,ID,LO,PA,MA,MAV,
     +ACS,CDD,AT,EPS,PRN,R,CD,CFVAC,STROKE
      PI=3.1415926536
      RIO=ID/2.
      ROO=OD/2.
      RI=RIO+X
      RO=ROO-X
      L=LO-2.*X
      SURF=0.
      IF(L.LE.0..OR.RO.LE.RI) RETURN
      SURF=2.*PI*(RO+RI)*(L+RO-RI)*N
      RETURN
      END
 -END OF FILE
?
```

```
 TAPE5

   700.            .125            .0166667      .5       1140000.
    10.           3.28             .0001         .6          5750.
     1.22        28.12          300.          200.             50.
     3.             .1             .525         5.5             6.
```

PROPELLANT THERMODYNAMIC DATA
FLAME TEMP = 5750.00 DEG R
SPECIFIC HEAT RATIO =1.2200
MOLECULAR WEIGHT = 28.12
EXIT TO CHAMBER PRESSURE RATIO =.02678
VACUUM THRUST COEFFICIENT =1.6516
SOUND SPEED = 3521.47 FT/S
DISCHARGE COEFFICIENT = .006584 LBM/S-LBF
PROPELLANT DENSITY = .06107 LBM/CU IN
BURNING RATE EXPONENT =.60000
BURNING RATE COEFFICIENT = .02367003 IN/S-PSIA

GEOMETRIC PROPELLANT DATA
NUMBER OF MONOPERF GRAINS = 700.
OD =1.5000 IN
ID = .2000 IN
LENGTH = 6.00000 IN

SYSTEM DATA
DEPTH = 300. FT
SYSTEM MASS =200.00 SLUGS
SYSTEM VIRTUAL MASS = 50.00 SLUGS
PROPELLANT MASS = 13.8376 SLUGS
SYSTEM CROSS SECTIONAL AREA = 3.0000 SQ FT
STROKE = 6.0000 FT
INITIAL FREE VOLUME = 10.0000 FT
ROCKET THROAT AREA = .52500 SQ FT
ANCHOR DRAG COEFFICIENT = .100000
NOZZLE AREA RATIO = 5.5000

TIME (SEC)	WEB BURN (IN)	GAS MASS (SLUG)	PROP MASS (SLUG)	VELOCITY (FT/S)	DISTANCE (FT)	GAS VOL (CU FT)	PRESSURE (PSIA)	THRUST (POUNDS)
0.000000	0.000000	1.416690	13.8376	0.0000	0.0000	10.0000	10000.00	1187095.
.001000	.006086	1.542516	13.6768	4.6894	.0023	10.0874	10793.82	1286213.
.002000	.012444	1.667873	13.5038	9.7528	.0095	10.1784	11566.72	1382720.
.003000	.019058	1.792264	13.3190	15.1804	.0219	10.2726	12315.33	1476194.
.004000	.025913	1.915256	13.1229	20.9605	.0400	10.3699	13036.98	1566300.
.005000	.032995	2.036472	12.9158	27.0805	.0640	10.4700	13729.57	1652780.

.006000	.040291	2.155592	12.6983	33.5269	.0943	10.5726	14391.56	1735438.
.007000	.047785	2.272341	12.4707	40.2855	.1311	10.6776	15021.89	1814142.
.008000	.055466	2.386491	12.2337	47.3419	.1749	10.7847	15619.87	1888808.
.009000	.063320	2.497851	11.9876	54.6810	.2259	10.8937	16185.20	1959397.
.010000	.071337	2.606266	11.7331	62.2880	.2844	11.0043	16717.87	2025908.
.011000	.079503	2.711609	11.4705	70.1479	.3506	11.1165	17218.10	2088368.
.012000	.087808	2.813783	11.2005	78.2459	.4247	11.2299	17686.35	2146835.
.013000	.096241	2.912713	10.9235	86.5673	.5071	11.3446	18123.21	2201382.
.014000	.104794	3.008347	10.6399	95.0978	.5980	11.4602	18529.43	2252105.
.015000	.113455	3.100648	10.3503	103.8233	.6974	11.5766	18905.87	2299108.
.016000	.122216	3.189597	10.0552	112.7302	.8057	11.6937	19253.45	2342507.
.017000	.131069	3.275189	9.7548	121.8053	.9229	11.8114	19573.15	2382427.
.018000	.140006	3.357428	9.4497	131.0356	1.0493	11.9295	19866.01	2418994.
.019000	.149018	3.436330	9.1403	140.4089	1.1850	12.0479	20133.08	2452340.
.020000	.158099	3.511920	8.8269	149.9131	1.3302	12.1664	20375.40	2482598.
.021000	.167242	3.584230	8.5100	159.5368	1.4849	12.2851	20594.06	2509900.
.022000	.176440	3.653298	8.1899	169.2689	1.6493	12.4038	20790.10	2534378.
.023000	.185688	3.719166	7.8669	179.0990	1.8235	12.5223	20964.56	2556162.
.024000	.194979	3.781881	7.5414	189.0166	2.0075	12.6407	21118.46	2575378.
.025000	.204308	3.841496	7.2136	199.0128	2.2015	12.7588	21252.79	2592150.
.026000	.213670	3.898063	6.8839	209.0776	2.4056	12.8766	21368.51	2606600.
.027000	.223060	3.951639	6.5526	219.2024	2.6197	12.9939	21466.56	2618843.
.028000	.232474	4.002282	6.2198	229.3787	2.8440	13.1108	21547.84	2628992.
.029000	.241907	4.050051	5.8860	239.5986	3.0785	13.2271	21613.22	2637156.
.030000	.251355	4.095008	5.5512	249.8543	3.3232	13.3429	21663.53	2643437.
.031000	.260815	4.137213	5.2158	260.1386	3.5782	13.4580	21699.57	2647937.
.032000	.270282	4.176728	4.8799	270.4445	3.8435	13.5725	21722.09	2650750.
.033000	.279753	4.213615	4.5438	280.7652	4.1191	13.6862	21731.85	2651967.
.034000	.289225	4.247937	4.2076	291.0947	4.4050	13.7992	21729.52	2651677.
.035000	.298696	4.279756	3.8715	301.4267	4.7013	13.9113	21715.78	2649961.
.036000	.308161	4.309132	3.5358	311.7557	5.0079	14.0227	21691.26	2646899.
.037000	.317618	4.336128	3.2005	322.0761	5.3248	14.1331	21656.56	2642567.
.038000	.325019	4.283774	2.8664	332.3644	5.6520	14.2190	21265.82	2593778.
.039000	.325019	3.967112	2.5497	342.1007	5.9893	14.2190	19693.83	2397494.
.039031	.325019	3.957591	2.5402	342.3930	6.0000	14.2190	19646.56	2391593.

```
DO YOU WANT TO STOP (.T.) OR CONTINUE (.F.) COMPUTING?
? .T.
```

APPENDIX C

WATER JET COMPUTER PROGRAM, INCLUDING ITS DESCRIPTION AND A SAMPLE CALCULATION

The flow equations and their derivatives were not included in the main text because their derivation is too lengthy and complex. This appendix also includes the computer program which evaluates these equations and gives a detailed view of the events that happen during the .040 seconds of a launch. The input data and a typical run are included.

Only two of the Navier Stokes Equations are needed because the flow is incompressible. The two equations needed are the equations of conservation of mass and momentum. The equation for the conservation of mass is

C-1 $$\rho\, A(z)\, U(z,t) = \rho\, A(x)\, U(x,t) \, .$$

Since the flow is incompressible, the densities on both sides of Eqn. C-1 are equal and can be canceled. It is more convenient to express the flow areas, A(z) and A(x), as the product of the main barrel flow area, A_0, and a function G(x) or G(z). The term, G(z), gives the flow area at any point along the length, z, as a fraction of A_0. With the water tube shape discussed in the text, G(z) has a value of 1 through the straight portion of the tube and less than one in the convergent nozzle. G(x) represents the area at x, the position of the gas-water interface. Again, both sides have equal terms, A_0, and they can be canceled. This simplifies Eqn. C-1 to

C-2 $$G(z)\, U(z,t) = G(x)\, U(x,t) \, .$$

The one-dimensional momentum equation is

C-3 $$\frac{1}{\rho}\,\frac{\partial P(z,t)}{\partial z} + \frac{\partial U(z,t)}{\partial t} + U(z,t)\,\frac{\partial U(z,t)}{\partial z} = 0 \, .$$

Rearranging Eqn. C-2 gives

C-4 $$U(z,t) = U(x,t)\,\frac{G(x)}{G(z)} \, .$$

Taking a partial derivative with respect to z gives

C-5 $$\frac{\partial U(z,t)}{\partial z} = - U(x,t)\, G(x)\, \frac{G'(z)}{G^2(z)} ,$$

where $$G'(z) = \frac{dG(z)}{dz} .$$

Taking a partial derivative of U(z) with respect to t gives

C-6 $$\frac{\partial U(z,t)}{\partial t} = \frac{dU(x,t)}{dt}\,\frac{G(x)}{G(z)} + U^2(x,t)\,\frac{G'(x)}{G(z)} .$$

The reader should be warned that U(x,t) is not standard notation. It is used to signify the water velocity at any time where z=x. That explains why there is no derivative with repect to z and why the derivative with respect to time is not a partial derivative. Substituting Equations C-4, 5, and 6 into Equation C-3 gives

C-7 $$\frac{1}{\rho}\,\frac{\partial P(z,t)}{\partial z} + \frac{dU(x,t)}{dt}\,\frac{G(x)}{G(z)} + U^2(x,t)\,\frac{G'(x)}{G(z)} - U^2(x,t)\, G^2(x)\,\frac{G'(z)}{G^3(z)} = 0 .$$

Now multiply Eqn. C-7 by dz and integrate over z from x to L.

C-8 $$-\frac{P(x,t) - P(L,t)}{\rho} + G(x)\,\frac{dU(x,t)}{dt}\int_x^L \frac{dz}{G(z)} + U^2(x,t)\, G'(x)\int_x^L \frac{dz}{G(z)} + U^2(x,t)\, G^2(x)\left[\frac{1}{G^2(L)} - \frac{1}{G^2(x)}\right] = 0 .$$

Now solve Eqn. C-8 for $\frac{dU(x,t)}{dt}$.

C-9 $$\frac{dU(x,t)}{dt} = \frac{P(x,t) - P(L,t) - \frac{1}{2}\rho\, U^2(x,t)\left[1 - \frac{G^2(x)}{G^2(L)}\right]}{\rho\, G(x)\int_x^L \frac{dz}{G(z)}} - U^2(x,t)\,\frac{G'(x)}{G(x)} .$$

Eqn. C-9 can be integrated with respect to time to give the velocity of the gas-water interface as a function of time. This velocity, in turn, can be integrated with respect to time to give the position of the gas-water interface as a function of time. In order to integrate Eqn. C-9, one needs to be able to calculate the pressure P at x and L for all times in the domain of the

calculation. Similarly, one needs a function for G(z) so that G(x), G(L), G'(x), and the integral of the reciprocal of G(z) from x to L. G(z) has a constant value of one (1) for values of z from zero to L_s; therefore, G'(z) equals zero over that range of z. The value of G(z) decreases monotonically from one to the minimum value as z goes from L_s to L. Consequently, the value of G'(z) is negative in this range. Because G(z) is determined by two different functions in the two regions, it is necessary to evaluate the integral of the reciprocal of G(z) in two steps. (This breakup should only be used when x is less than L_s.)

C-10 $$\int_x^L \frac{dz}{G(z)} = \int_x^{L_s} \frac{dz}{G(z)} + \int_{L_s}^L \frac{dz}{G(z)}, \quad \text{where} \quad x < L_s .$$

G(z) has a constant value of one (1) while z is in the interval from zero to L_s. Therefore, the first integral on the right-hand side of Eqn. C-10 simplifies to the integral of dz over the same range. That integral reduces to $L_s - x$.

C-11 $$\int_x^L \frac{dz}{G(z)} = L_s - x + \int_{L_s}^L \frac{dz}{G(z)}, \quad \text{where} \quad x < L_s .$$

When x is greater than L_s, the integral is not broken up. It is evaluated by integrating directly from x to L.

To calculate x, the distance traveled by the gas-water interface, it is necessary to integrate the following equations.

C-12 $$\frac{dx}{dt} = U(x,t)$$

The boundary conditions for the velocity and the distance are

C-13	$U(x,t) = 0$	when $t = 0$
C-14	$x = 0$	when $t = 0$

As with the other two PEA options, it is necessary to be able to calculate the pressures, P(x,t) and P(L,t). In an all-up analysis, the pressures would be calculated from first principles as was done for the recoilless and direct rocket PEAs. This was not done for the water jet PEA computer program. The pressures were set to constant values. Even though the actual

pressure would not be precisely constant, it would not be very far off. This simplification saved time and permitted many runs to be compared without the secondary effects of pressure variation blurring the relationships.

There is another shortcoming in the analysis as it is presented here. No account is taken of the mass of the propellant gas in the dynamic equations. Some of the energy from the expanding gas must be used to accelerate the gas as well as the water. The density of the gas is about one tenth that of water when the pressure is 10,000 psi and two tenths when the pressure is 20,000 psi. The added mass of the gas is insignificant at the start of the cycle when most of the tube is filled with water. Although the quantity of gas is greater during the main mid-portion of the run, it is also insignificant there because the acceleration is zero then. The only time that it has a significant effect is very near the end of the cycle, when there is very little water and the mass of the gas exceeds that of the water. Only the last part of the cycle is significantly affected by the mass of the gas. The acceleration of the interface would be very high and approach infinity as the denominator of the main term in Equation C-9 goes to zero. In reality, the mass of the gas would prevent this from happening, but that mass does not show in Equation C-9. The computer program in this appendix handles this in a nonrigorous, but effective, way.

Equation C-9 gives the acceleration of the gas water interface. If one multiplies the numerator and denominator of the main term by the term A_0, then one can see that that first term is a force divided by a mass (an acceleration). In the enclosed program, the mass of the gas is given as the product of the mass density of the water and the effective length of the gas column. (Again A_0 has been factored out.) In the program, this mass of gas per unit area is added to the mass of water per unit area in the denominator of the main term.

```
      PROGRAM PEA(INPUT,OUTPUT)
      COMMON L,LN,GL,RHO,PX,PL,AO
      DIMENSION Y(30),NTERM(5),TERM(5)
      REAL I,L,LS,LN,NINTS
      LOGICAL BEDONE
      EXTERNAL DERIV
      NAMELIST /AGAIN/PX,DEPTH,L,LN,GL,AO,TSTEP,NPRINT
      RHO=1.9545
      BEDONE=.F.
      PRINT 50
   50 FORMAT('1 TYPE IN VALUES FOR PX,DEPTH,L,LN,GL,AO,TSTEP,NPRINT')
      READ *,PX,DEPTH,L,LN,GL,AO,TSTEP,NPRINT
  100 LS=L-LN
      PL=14.7+DEPTH*.4367
      DO 200 J=1,30
  200 Y(J)=0.
      PRINT 300,PX,PL,DEPTH,L,LN,AO,GL*AO,TSTEP
  300 FORMAT('1 INPUT DATA'/5X'DRIVE PRESSURE ='F10.2' PSIA'/5X
     A'AMBIENT PRESSURE ='F10.2' PSIA'/5X'DEPTH = 'F6.0' FEET'/5X
     B'TUBE LENGTH ='F8.4' FEET'/5X'NOZZLE LENGTH'F8.4' FEET'/5X
     C'CHANNEL CROSS SECTION ='F8.4' SQ FEET'/5X'NOZZLE AREA ='F8.4
     D' SQ FEET'/5X'INTEGRATION STEP ='E10.3' SEC'
     E///6X'TIME DISTANCE'6X'V(X)'6X'V(Y)    THRUST   IMPULSE'/
     F5X'(SEC)    (FEET)     (FT/S)     (FT/S)   (POUND)    (LB-S)'//)
      NTERM(1)=3
      TERM(1)=.9999L
      CALL RUINT(4,TSTEP,NPRINT,.T.,Y,1,NTERM,TERM,DERIV)
      PRINT 400
  400 FORMAT(/////)
      READ AGAIN
      IF(.NOT.BEDONE) GO TO 100
      END


      SUBROUTINE RUINT(NUM,H,NPRINT,INIT,YNEW,NTC,NTERM,TERM,DERIV)
      DIMENSION YNEW(30),YOLD(30),D(30),B(4),Q(4,30),NTERM(30),
     + TERM(30)
      INTEGER COUNT
      LOGICAL INIT
      EQUIVALENCE(YOLD(1),TOLD)
      DATA B(1),B(2)/.5,.5/,B(3),B(4)/1.,1./,COUNT,N/0,0/,D(1)/1./
      HH=-HH
      HSAVE=0.
      N=COUNT+MOD(N-COUNT,NPRINT)
      NTC=1
      IF(.NOT.INIT) GO TO 100
      CALL PRINT(NUM,YNEW)
      COUNT=0
      N=NPRINT
50     HH=H
100    DO 150 J=1,NUM
```

```
150    YOLD(J)=YNEW(J)
      DO 250 J=1,4
      CALL DERIV(NUM,YNEW.D)
      DO 200 I=1,NUM
      Q(J,I)=D(I)*HH
200    YNEW(I)=YOLD(I)+Q(J,I)*B(J)
250    CONTINUE
      DO 300 I=1,NUM
300    YNEW(I)=YOLD(I)+(Q(1,I)+Q(4,I))/6.+(Q(2,I)+Q(3,I))/3.
      IF(MTC.GT.NTC) GO TO 380
      DO 375 J=MTC,NTC
      LTC=IABS(NTERM(J))
      IF(YNEW(LTC)*NTERM(J).LT.TERM(J)*NTERM(J)) GO TO 375
      MTC=J+1
      HH=(TERM(J)-YNEW(LTC))/D(LTC)
      HSAVE=HSAVE+HH
      GO TO '00
375    CONTINUE
380    CONTINUE
      IF(HH.GT.0.) GO TO 400
      CALL PRINT (NUM.YNEW)
      HH=HSAVE
      RETURN
400    COUNT =COUNT+1
      IF (COUNT.NE.N)GO TO 50
      CALL PRINT (NUM, YNEW)
      N=N+NPRINT
      GO TO 50
      END
```

```
      SUBROUTINE DERIV(NUM.Y.D)
      COMMON L.LN.GL.RHO.PX.PL.AO
      REAL L.LN.LS
      DIMENSION Y(30).D(30)
      D(1)=1.
      CALL NOZ(Y(3),GX,GPRIME,GINT,RAT)
      D(2)=((PX-PL)*144./RHO+.5*Y(2)**2*(1.-(GX/GL)**2-RAT*(1.-GX**2)))
     A/GX/GINT-Y(2)**2*GPRIME/GX
      D(3)=Y(2)
      D(4)=RHO*AO*GX*((L-Y(3))*D(2)+Y(2)**2*(GX/GL-1.))
      Y(20)=D(4)
      Y(21)=Y(2)*GX/GL
      RETURN
      END
```

```
      SUBROUTINE NOZ(X,GX,GPRIME,GINT,RAT)
      COMMON L,LN,GL,RHO,PX,PL,AO
      REAL L,LN,LS
      LS=L-LN
      IF(X.GT.L*.999999999) X=L*.999999999
      PI=3.14159
      RAT=PX*6.24E-6
      GPRIME=0.
      GX=1.
      GINT=RAT*X+LS-X+LN/SQRT(GL)
      IF(X.LE.LS) RETURN
      GX=(1.+GL)/2.+(1.-GL)/2.*COS(PI*(X-LS)/LN)
      GPRIME=(GL-1.)*PI/2./LN*SIN(PI*(X-LS)/LN)
      TERM=2.*LN/PI/SQRT(GL)*ATAN(SQRT(GL)*TAN(PI*(X-LS)/2./LN))
      GINT=RAT*(LS+TERM)+LN/SQRT(GL)-TERM
      RETURN
      END

      SUBROUTINE PRINT(NUM,Y)
      DIMENSION Y(30)
      PRINT 100,Y(1),Y(3),Y(2),Y(21),Y(20),Y(4)
  100 FORMAT(F10.6,F10.4,2F10.3,2E10.3)
      RETURN
      END
```

```
 1.GO
1 TYPE IN VALUES FOR PX,DEPTH,L,LN,GL,AO,TSTEP,NPRINT
? 20000.,300.,7.,1.,.1,2.65,.00001,100
1 INPUT DATA
    DRIVE PRESSURE =  20000.00 PSIA
    AMBIENT PRESSURE =    145.71 PSIA
    DEPTH =   300. FEET
    TUBE LENGTH =  7.0000 FEET
    NOZZLE LENGTH  1.0000 FEET
    CHANNEL CROSS SECTION =  2.6500 SQ FEET
    NOZZLE AREA =   .2650 SQ FEET
    INTEGRATION STEP =  .100E-04 SEC
```

TIME (SEC)	DISTANCE (FEET)	V(X) (FT/S)	V(Y) (FT/S)	THRUST (POUND)	IMPULSE (LB-S)
0.000000	0.0000	0.000	0.000	0.	0.
.001000	.0705	125.667	1256.668	.342E+07	.484E+04
.002000	.2203	163.966	1639.658	.177E+07	.725E+04
.003000	.3886	170.709	1707.092	.144E+07	.881E+04
.004000	.5600	171.733	1717.334	.139E+07	.102E+05
.005000	.7318	171.881	1718.811	.138E+07	.116E+05
.006000	.9037	171.902	1719.016	.138E+07	.130E+05
.007000	1.0756	171.904	1719.044	.138E+07	.143E+05
.008000	1.2475	171.905	1719.047	.138E+07	.157E+05
.009000	1.4194	171.905	1719.048	.138E+07	.171E+05
.010000	1.5913	171.905	1719.048	.138E+07	.185E+05
.011000	1.7632	171.905	1719.048	.138E+07	.199E+05
.012000	1.9351	171.905	1719.048	.138E+07	.212E+05
.013000	2.1070	171.905	1719.048	.138E+07	.226E+05
.014000	2.2789	171.905	1719.048	.138E+07	.240E+05
.015000	2.4508	171.905	1719.048	.138E+07	.254E+05
.016000	2.6227	171.905	1719.048	.138E+07	.267E+05
.017000	2.7946	171.905	1719.048	.138E+07	.281E+05
.018000	2.9665	171.905	1719.048	.138E+07	.295E+05
.019000	3.1384	171.905	1719.048	.138E+07	.309E+05
.020000	3.3104	171.905	1719.048	.138E+07	.323E+05
.021000	3.4823	171.905	1719.048	.138E+07	.336E+05
.022000	3.6542	171.905	1719.048	.138E+07	.350E+05
.023000	3.8261	171.905	1719.048	.138E+07	.364E+05
.024000	3.9980	171.905	1719.048	.138E+07	.378E+05
.025000	4.1699	171.905	1719.048	.138E+07	.391E+05
.026000	4.3418	171.905	1719.048	.138E+07	.405E+05
.027000	4.5137	171.905	1719.048	.138E+07	.419E+05
.028000	4.6856	171.905	1719.048	.138E+07	.433E+05
.029000	4.8575	171.905	1719.048	.138E+07	.447E+05
.030000	5.0294	171.905	1719.048	.138E+07	.460E+05
.031000	5.2013	171.905	1719.048	.138E+07	.474E+05
.032000	5.3732	171.905	1719.048	.138E+07	.488E+05
.033000	5.5451	171.905	1719.048	.138E+07	.502E+05
.034000	5.7170	171.905	1719.048	.138E+07	.515E+05
.035000	5.8889	171.905	1719.048	.138E+07	.529E+05
.036000	6.0610	173.337	1719.094	.142E+07	.543E+05
.037000	6.2431	196.648	1720.661	.151E+07	.558E+05
.038000	6.4769	296.886	1729.629	.163E+07	.573E+05
.038808	6.9930	2235.200	2257.625	.428E+05	.586E+05

APPENDIX D

SYSTEM SIZE AND WEIGHT COMPUTER PROGRAM, INCLUDING ITS DESCRIPTION AND A SAMPLE CALCULATION

The BASIC computer program included in this appendix calculates a matrix of weights and dimensions of water jet PEA launchers. The program was coded to assume that all of the water jet launchers had to deliver 5.76×10^4 foot-pounds of impulse at a thrust level of 1.44×10^6 pounds. It also assumes that all of the launchers are made of steel with a weight density of 492 pounds per cubic foot. Within these constraints, the weights and dimensions of the water jet PEA launcher were calculated for a matrix of values of the inside diameter of the water tube, the driving pressure, and the yield stress of the structural material.

Four equations from the main text are needed to calculate the dependent variables. Equation E-I-1 is needed to calculate the inside diameter of the launch tube; Equation E-I-5 to calculate the weight of the launch tube; Equation E-I-10 to calculate the length of the water tube; and Equation E-I-13 to calculate the weight of the water tube. The total system weight calculated in this program does not include the weights of the anchor, piston, propellant, or water. It is the sum of the weights of the launch tube and the water tube.

```
00100 MARGIN 132
00110 R1 = 1.9887
00120 READ I3,T, RO
00130 READ P1,P2,P3
00140 READ D1,D2,D3
00150 READ S1,S2,S3
00160 P9=4*ATN(1)
00170 FOR D=D1 TO D2 STEP D3
00180 A=P9*D^2/4
00190 PRINT "INSIDE DIAMETER OF WATER TUBE ="D" FEET.  ";
00200 PRINT "WATER TUBE CROSS SECTIONAL AREA ="A" SQUARE FEET. "
00210 PRINT "TOTAL IMPULSE ="I3" POUND SECONDS."
00220 PRINT "THRUST ="T" POUNDS."
00230 PRINT
00240 PRINT TAB(21);"WATER TUBE"
00250 PRINT "       P-PA BARREL ID    LENGTH  ";
00260 PRINT "(-----------------------------TOTAL SYSTEM WEI";
00270 PRINT "GHT--------------------------------."
00280 PRINT "     (PSI)    (FEET)    (FEET)";
00290 PRINT "  ------------------------------------(POUNDS";
00300 PRINT ")--------------------------------------- "
00310 PRINT
00320 PRINT "YIELD STRESSES (PSI)---------->";
00330 FOR S=S1 TO S2 STEP S3
00340 PRINT USING "########",S/144;
00350 NEXT S
00360 PRINT
00370 PRINT
00380 FOR P=P1 TO P2 STEP P3
00390 V=I3/SQR(2*R1*(P-T/A))
00400 L=V/A+D/3
00410 PRINT USING  00420, P/144;SQR(T*4/P/P9);L;
00420 : ########## #####.### ######.##
00430 FOR S=S1 TO S2 STEP S3
00440 W0=RO*12*T/(S-2*P)
00450 W=RO*P*D*(2*(L-D)/(S-2*P)+9/(S-1.5*P))+W0
00460 PRINT USING  00470,W;
00470 : #######
00480 NEXT S
00490 PRINT
```

```
00500 NEXT P
00510 PRINT
00520 PRINT TAB(21);"WATER TUBE"
00530 PRINT "      P-PA BARREL ID    LENGTH  ";
00540 PRINT "<-----------------------------------BARREL WEI";
00550 PRINT "GHT------------------------------------->"
00560 PRINT "     (PSI)    (FEET)    (FEET)";
00570 PRINT "  <--------------------------------------(POUNDS";
00580 PRINT ")---------------------------------------->"
00590 PRINT
00600 PRINT "YIELD STRESSES (PSI)---------->";
00610 FOR S=S1 TO S2 STEP S3
00620 PRINT USING "########",S/144;
00630 NEXT S
00640 PRINT
00650 PRINT
00660 FOR P=P1 TO P2 STEP P3
00670 V=I3/SQR(2*R1*(P-T/A))
00680 L=V/A+D/3
00690 PRINT USING  00700, P/144;SQR(T*4/P/P9);L;
00700 : ######### #####.### ######.##
00710 FOR S=S1 TO S2 STEP S3
00720 W0=R0*12*T/(S-2*P)
00730 PRINT USING  00740,W0;
00740 : #######
00750 NEXT S
00760 PRINT
00770 NEXT P
00780 PRINT
00790 PRINT
00800 NEXT D
00810 DATA 57600,1440000,492
00820 DATA 1440000,3600000,144000
00830 DATA 1.25,3,.25
00840 DATA 1.44 E7,2.88 E7,1.44 E6
00850 END
```

INSIDE DIAMETER OF WATER TUBE = 2.25 FEET. WATER TUBE CROSS SECTIONAL AREA = 3.97608 SQUARE FEET,
TOTAL IMPULSE = 57600 POUND SECONDS.
THRUST = 1440000 POUNDS.

P-PA (PSI)	BARREL ID (FEET)	WATER TUBE LENGTH (FEET)	TOTAL SYSTEM WEIGHT (POUNDS)										
YIELD STRESSES (PSI)			100000	110000	120000	130000	140000	150000	160000	170000	180000	190000	200000
10000	1.128	7.75	2552	2270	2044	1859	1705	1574	1452	1365	1280	1205	1138
11000	1.076	7.32	2668	2367	2127	1931	1768	1631	1513	1411	1322	1244	1174
12000	1.030	6.97	2789	2468	2213	2005	1833	1689	1565	1459	1366	1284	1211
13000	.990	6.66	2915	2572	2301	2081	1900	1748	1618	1506	1409	1324	1248
14000	.954	6.40	3047	2679	2391	2159	1968	1808	1672	1555	1453	1364	1285
15000	.921	6.17	3184	2791	2484	2238	2037	1869	1726	1604	1498	1405	1323
16000	.892	5.96	3326	2906	2580	2320	2107	1931	1781	1653	1543	1446	1360
17000	.865	5.78	3475	3025	2679	2403	2180	1994	1837	1703	1588	1487	1398
18000	.841	5.61	3631	3149	2781	2489	2253	2058	1894	1754	1634	1529	1436
19000	.819	5.46	3795	3278	2886	2577	2328	2124	1952	1806	1680	1571	1475
20000	.798	5.33	3967	3413	2995	2668	2406	2190	2010	1858	1727	1613	1513
21000	.779	5.20	4148	3553	3107	2761	2485	2258	2070	1911	1774	1656	1552
22000	.761	5.09	4339	3699	3224	2857	2566	2328	2131	1965	1822	1699	1592
23000	.744	4.98	4541	3852	3345	2957	2649	2400	2193	2019	1871	1743	1632
24000	.728	4.88	4756	4013	3472	3059	2735	2473	2256	2075	1920	1787	1672
25000	.714	4.79	4985	4183	3604	3166	2823	2548	2321	2132	1971	1832	1712

P-PA (PSI)	BARREL ID (FEET)	WATER TUBE LENGTH (FEET)	BARREL WEIGHT (POUNDS)										
YIELD STRESSES (PSI)			100000	110000	120000	130000	140000	150000	160000	170000	180000	190000	200000
10000	1.128	7.75	738	656	590	536	492	454	421	393	369	347	328
11000	1.076	7.32	756	670	602	546	500	461	427	398	373	351	331
12000	1.030	6.97	776	686	615	556	508	468	434	404	378	355	335
13000	.990	6.66	797	702	628	567	517	476	440	410	383	360	339
14000	.954	6.40	820	720	641	578	527	483	447	415	388	364	343
15000	.921	6.17	843	738	656	590	536	492	454	421	393	369	347
16000	.892	5.96	868	756	670	602	546	500	461	427	398	373	351
17000	.865	5.78	894	776	686	615	556	508	468	434	404	378	355
18000	.841	5.61	922	797	702	628	567	517	476	440	410	383	360
19000	.817	5.46	952	820	720	641	578	527	483	447	415	388	364
20000	.798	5.33	984	843	738	656	590	536	492	454	421	393	369
21000	.779	5.20	1017	868	756	670	602	546	500	461	427	398	373
22000	.761	5.09	1054	894	776	686	615	556	508	468	434	404	378
23000	.744	4.98	1093	922	797	702	628	567	517	476	440	410	383
24000	.728	4.88	1135	952	820	720	641	578	527	483	447	415	388
25000	.714	4.79	1180	984	843	738	656	590	536	492	454	421	393

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